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# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**DESIGN OF EXPERIMENT AND ANALYSIS FOR THE  
JOINT DYNAMIC ALLOCATION OF FIRES AND  
SENSORS (JDAFS) SIMULATION**

by

Jeffrey T. Freye

June 2007

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**DESIGN OF EXPERIMENT ANALYSIS FOR THE JOINT DYNAMIC  
ALLOCATION OF FIRES AND SENSORS (JDAFS) SIMULATION**

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**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

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## **ABSTRACT**

The U.S. Army Training and Doctrine Command (TRADOC) Analysis Center's Joint Dynamic Allocation of Fires and Sensors (JDAFS) model, a low-resolution, Discrete Event Simulation Model with embedded optimization enables the analysis of many scenarios and factors to explore Joint Intelligence, Surveillance, and Reconnaissance (ISR) missions. JDAFS is a powerful model that combines both discrete event simulation and the optimization of a linear objective function to generate realistic, reasonable, and consistent solutions to difficult ISR scheduling problems. Given a scenario and a mix of ISR platforms, JDAFS optimizes a flight schedule and executes the missions. This research develops a Joint ISR scenario, explores scenario simulation results, and provides a proof-of-principle analysis that aids in the ISR decision making process.

This study examines 274 design points in each of two scenarios, a non-penetrating scenario that allows only standoff collection and a penetrating scenario that allows country of interest overflight. The use of an efficient design of experiment methodology enables the exploration of the interior and exterior of the response surface for the two experimental scenarios. Analysis of the simulation output suggests that the optimization interval significantly impacts total coverage. In the non-penetrating scenario, shorter optimization intervals ensure better coverage; however, in the penetrating scenario, longer optimization intervals provide for improved coverage. The disparity is explained by reduced likelihood of assignment saturation in the penetrating scenario due to the increased number of mission areas. Sensor range, sensor package configuration, and platform dwell time also affect the level of coverage. This is clearly demonstrated by the superior coverage provided by the most capable ISR platforms.



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## **DISCLAIMER**

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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# TABLE OF CONTENTS

<b>I.</b>	<b>INTRODUCTION.....</b>	<b>1</b>
<b>A.</b>	<b>BACKGROUND .....</b>	<b>1</b>
<b>B.</b>	<b>PURPOSE OF RESEARCH .....</b>	<b>3</b>
<b>C.</b>	<b>RESEARCH QUESTIONS .....</b>	<b>3</b>
<b>D.</b>	<b>SCOPE OF RESEARCH .....</b>	<b>3</b>
<b>E.</b>	<b>THESIS ORGANIZATION.....</b>	<b>4</b>
<b>II.</b>	<b>JDAFS MODEL, INPUTS AND METHODOLOGY .....</b>	<b>5</b>
<b>A.</b>	<b>HISTORY OF THE JDAFS MODEL.....</b>	<b>5</b>
<b>B.</b>	<b>JDAFS ORIGINAL CONFIGURATION.....</b>	<b>5</b>
	<b>1. JDAFS Functionality .....</b>	<b>6</b>
	<b>2. Event Graph Methodology .....</b>	<b>6</b>
<b>C.</b>	<b>ASC-U ORIGINAL CONFIGURATION.....</b>	<b>7</b>
	<b>1. Primary ASC-U Components .....</b>	<b>8</b>
	<i>a. Missions.....</i>	<i>8</i>
	<i>b. ISR Platforms.....</i>	<i>8</i>
	<i>c. Sensor Packages.....</i>	<i>9</i>
	<i>d. LRS .....</i>	<i>9</i>
	<i>e. GCS.....</i>	<i>9</i>
	<b>2. Simulation and Optimization.....</b>	<b>9</b>
	<b>3. ASC-U Platform Assignment Process .....</b>	<b>10</b>
<b>D.</b>	<b>CHANGES IMPLEMENTED IN JDAFS .....</b>	<b>14</b>
	<b>1. Scheduling Tool.....</b>	<b>14</b>
	<b>2. Mission Areas .....</b>	<b>15</b>
	<b>3. Bases .....</b>	<b>15</b>
<b>E.</b>	<b>IMPROVED JDAFS CONFIGURATION .....</b>	<b>15</b>
	<b>1. LOS Calculation.....</b>	<b>15</b>
	<b>2. Input Requirements.....</b>	<b>16</b>
	<i>a. DAFSScenario .....</i>	<i>17</i>
	<i>b. GCS.....</i>	<i>17</i>
	<i>c. GCSLocation .....</i>	<i>18</i>
	<i>d. LinearKillProbability .....</i>	<i>18</i>
	<i>e. LOS .....</i>	<i>19</i>
	<i>f. LRS .....</i>	<i>19</i>
	<i>g. LRSLocation.....</i>	<i>19</i>
	<i>h. MetaData .....</i>	<i>20</i>
	<i>i. Mission .....</i>	<i>20</i>
	<i>j. MissionArea .....</i>	<i>21</i>
	<i>k. MissionPackageLocation.....</i>	<i>21</i>
	<i>l. MissionPackageType .....</i>	<i>21</i>
	<i>m. MissionPlatformLocation .....</i>	<i>22</i>
	<i>n. MissionPlatformType.....</i>	<i>22</i>
	<i>o. Mover.....</i>	<i>23</i>

	<i>p.</i>	<i>MoverManager</i> .....	24
	<i>q.</i>	<i>Munition</i> .....	24
	<i>r.</i>	<i>MunitionType</i> .....	25
	<i>s.</i>	<i>PlatformType</i> .....	25
	<i>t.</i>	<i>Route</i> .....	25
	<i>u.</i>	<i>Sensor</i> .....	26
	<i>v.</i>	<i>SensorRange</i> .....	26
	<i>w.</i>	<i>SensorType</i> .....	27
	<i>x.</i>	<i>Side</i> .....	27
	<i>y.</i>	<i>SimEntity</i> .....	27
3.		Execution .....	27
4.		Output .....	28
	<i>a.</i>	<i>Coverage</i> .....	29
	<i>b.</i>	<i>Coverage by Type</i> .....	29
	<i>c.</i>	<i>KillerVictimScoreboard</i> .....	30
III.		SCENARIO DEVELOPMENT .....	31
A.		SCENARIOS .....	31
	1.	Missions (Targets).....	32
	2.	Mission Areas .....	33
	3.	Bases .....	34
	4.	Threats .....	34
B.		PLATFORMS .....	37
	1.	RQ-1 Predator .....	37
	2.	RQ-4 Global Hawk .....	37
	3.	P-3C Orion.....	38
	4.	RC-135 Rivet Joint.....	38
	5.	U-2 Dragon Lady.....	39
C.		SENSORS .....	40
	1.	Electro-Optical/Infrared (EO/IR) .....	40
	2.	SAR.....	40
	3.	SIGINT.....	41
	4.	Sensor Ranges.....	41
D.		CONSTRAINTS, LIMITATIONS, AND ASSUMPTIONS .....	42
	1.	Constraints.....	42
	2.	Limitations.....	43
	3.	Assumptions .....	43
IV.		MOE, DOE, AND RUN EXECUTION.....	45
A.		MEASURES OF EFFECTIVENESS (MOE).....	45
	1.	Coverage .....	45
	2.	Coverage by Type .....	46
	3.	Attrition .....	46
B.		DESIGN OF EXPERIMENT.....	47
	1.	Factors.....	48
		<i>a.</i> <i>Assets Assigned to Bases</i> .....	48
		<i>b.</i> <i>Optimization Interval</i> .....	49

2.	NOLH.....	50
C.	EXECUTION OF SCENARIOS .....	55
1.	Implementing DOE .....	55
2.	Computing Resources.....	57
3.	Post-processing of JDAFS Output.....	58
V.	ANALYSIS .....	61
A.	ANALYSIS METHODOLOGY, TECHNIQUES, AND TOOLS .....	61
1.	Methodology .....	61
2.	Analytical Techniques .....	61
a.	Spreadsheet Analysis.....	62
b.	Multiple Regression .....	62
c.	Classification and Regression Trees (CART) .....	64
d.	Graphical Analysis .....	64
3.	Analysis Tools.....	64
a.	Microsoft Excel .....	64
b.	JMP Statistical Discovery Software .....	65
B.	PRE-SIMULATION ANALYSIS.....	65
1.	Non-Penetrating Scenario .....	65
a.	Scenario Geometry.....	65
b.	Sensor Coverage.....	67
c.	Assessment.....	72
2.	Penetrating Scenario.....	73
a.	Scenario Geometry.....	73
b.	Sensor Coverage.....	74
c.	Assessment.....	80
C.	MEASURES OF EFFECTIVENESS (MOE).....	81
1.	Non-Penetrating Scenario Coverage .....	81
a.	Coverage Regression Model .....	81
b.	Coverage Factor Interactions.....	85
c.	Coverage Regression Tree Analysis .....	90
d.	Coverage Contour Plot Analysis.....	92
2.	Non-Penetrating Scenario Coverage by Type .....	93
3.	Penetrating Scenario Coverage .....	94
a.	Coverage Regression Model .....	94
b.	Coverage Factor Interactions.....	98
c.	Coverage Regression Tree Analysis .....	99
d.	Coverage Contour Plot Analysis.....	101
4.	Coverage by Type .....	104
5.	Attrition .....	105
6.	Comparison of Non-Penetrating vs. Penetrating Results.....	106
a.	Coverage .....	106
c.	Coverage by Type .....	107
b.	Factor Comparison .....	108
VI.	FINDINGS AND RECOMMENDATIONS .....	111
A.	SIGNIFICANT FINDINGS .....	111

1.	Data Analysis Issues.....	111
2.	Issues Identified and Corrected During Preliminary Testing .....	111
a.	<i>JDAFS Architectural Issues</i> .....	112
b.	<i>JDAFS Bugs Identified and Corrected</i> .....	112
B.	RECOMMENDATIONS FOR FURTHER JDAFS IMPROVEMENT.	113
C.	RECOMMENDATIONS FOR FUTURE JDAFS STUDIES .....	114
APPENDIX A. NON-PENETRATING SCENARIO BASE TO MISSION AREA DISTANCE TABLE .....		115
APPENDIX B. PENETRATING SCENARIO BASE TO MISSION AREA DISTANCE TABLE .....		117
APPENDIX C. BASE ‘A’ TRANSIT AND ON-STATION STATISTICS.....		119
APPENDIX D. BASE ‘B’ TRANSIT AND ON-STATION STATISTICS.....		121
APPENDIX E. BASE ‘C’ TRANSIT AND ON-STATION STATISTICS .....		123
APPENDIX F. BASE ‘D’ TRANSIT AND ON-STATION STATISTICS .....		125
APPENDIX G. NON-PENETRATING COVERAGE MODEL.....		127
APPENDIX H. PENETRATING COVERAGE MODEL .....		129
APPENDIX I. REGRESSION TREE FOR NON-PENETRATING COVERAGE .....		131
APPENDIX J. REGRESSION TREE FOR PENETRATING COVERAGE.....		133
LIST OF REFERENCES.....		135
INITIAL DISTRIBUTION LIST .....		139

## LIST OF FIGURES

Figure 1.	JDAFS Scenario.....	xxi
Figure 2.	Event Graph Example (From Buss and Ahner 2006b) .....	7
Figure 3.	ASC-U Dynamic Cueing and Transitions (From: Ahner et al. 2006a).....	10
Figure 4.	ASC-U Dynamic Cueing and Transitions (From: Ahner et al. 2006a).....	11
Figure 5.	Minimum Altitude Line-of-Sight Determination.....	16
Figure 6.	JDAFS Graphical User Interface .....	28
Figure 7.	JDAFS Non-Penetrating Scenario as Designed ( <i>Best viewed in color</i> ).....	35
Figure 8.	JDAFS Non-Penetrating Scenario in JDAFS GUI ( <i>Best viewed in color</i> ) .....	35
Figure 9.	JDAFS Penetrating Scenario as Designed ( <i>Best viewed in color</i> ).....	36
Figure 10.	JDAFS Penetrating Scenario in JDAFS GUI ( <i>Best viewed in color</i> ) .....	36
Figure 11.	RQ-1 Predator (From Global Aircraft 2007) .....	37
Figure 12.	RQ-4 Global Hawk (From Tech-Writer.net 2007, accessed 07 May 2007)....	37
Figure 13.	P-3C Orion (From Aerospaceweb.org 2007, accessed 07 May 2007) .....	38
Figure 14.	RC-135 Rivet Joint (From Aerospaceweb.org 2007, accessed 07 May 2007)).....	38
Figure 15.	U-2 Dragon Lady (From Aerospaceweb.org 2007, accessed 07 May 2007)...39	
Figure 16.	EO and IR Images over Bosnia (After Global Defense Review 1997) .....	40
Figure 17.	SAR Image of the Pentagon (After Sandia National Laboratories 2006).....	41
Figure 18.	Cookie-Cutter Sensor Footprints .....	42
Figure 19.	Coverage Data Table Example .....	45
Figure 20.	Coverage by Type Data Table Example .....	46
Figure 21.	Killer Victim Scoreboard Example.....	47
Figure 22.	Nearly Orthogonal Latin Hypercube Worksheet. ....	52
Figure 23.	Scatterplot Matrix for Design Factors.....	54
Figure 24.	Design Generator for Producing Input Files.....	57
Figure 25.	Output Generator for Producing Output Files .....	58
Figure 26.	Example of Mission Area-to-Mission Pairings for a Single Mission Area to all EO/IR Missions.....	66
Figure 27.	Basing Configuration .....	66
Figure 28.	RQ-1 Sensor Coverage for the Non-Penetrating Scenario .....	67
Figure 29.	RQ-4 Sensor Coverage for the Non-Penetrating Scenario .....	68
Figure 30.	P-3 Sensor Coverage for the Non-Penetrating Scenario.....	68
Figure 31.	RC-135 Sensor Coverage for the Non-Penetrating Scenario.....	69
Figure 32.	U-2 Sensor Coverage for the Non-Penetrating Scenario .....	69
Figure 33.	Potential Mission Coverage by ISR Platform.....	70
Figure 34.	Predicted Percentage of Time On-Station by Base and Platform Type.....	71
Figure 35.	Basing Configuration .....	74
Figure 36.	RQ-1 Sensor Coverage for the Penetrating Scenario.....	75
Figure 37.	RQ-4 Sensor Coverage for the Penetrating Scenario.....	75
Figure 38.	P-3 Sensor Coverage for the Penetrating Scenario .....	76
Figure 39.	RC-135 Sensor Coverage for the Penetrating Scenario.....	76
Figure 40.	U-2 Sensor Coverage for the Penetrating Scenario .....	77



Figure 41.	Potential Mission Coverage by ISR Platform.....	78
Figure 42.	Predicted Percentage of Time On-Station by Base and Platform Type.....	79
Figure 43.	Distribution and Summary Statistics of Mission Area Coverage .....	81
Figure 44.	Actual by Predicted Coverage Plot for Full Quadratic Model with Single Base Outliers Included.....	82
Figure 45.	Non-Penetrating Scenario: Distribution and Summary Statistics of Mission Area Coverage ( <i>single base outliers removed</i> ).....	83
Figure 46.	Actual by Predicted Coverage Plot for Full Quadratic Model with Single Base Outliers Removed.....	83
Figure 47.	Full Quadratic Coverage Model Terms .....	84
Figure 48.	Residual by Predicted Plot for Coverage Model.....	85
Figure 49.	Histogram and Normal Quantile Plot of Residuals for Coverage Model .....	85
Figure 50.	Interaction Profile for Final Coverage Model.....	86
Figure 51.	Interaction Profile for A RQ-4 and B RC-135.....	87
Figure 52.	Interaction Profile for A RC-135 and D RQ-4.....	87
Figure 53.	Interaction Profile for B RC-135 and A RQ-4.....	87
Figure 54.	Interaction Profile for B RC-135 and D RQ-4.....	88
Figure 55.	Interaction Profile for C RQ-4 and D U-2 .....	88
Figure 56.	Interaction Profile for D RQ-4 and A RC-135.....	88
Figure 57.	Interaction Profile for D RQ-4 and B RC-135.....	89
Figure 58.	Interaction Profile for D U-2 and C RQ-4 .....	89
Figure 59.	R-Squared vs. Number of Regression Tree Splits .....	90
Figure 60.	Regression Tree for Coverage .....	91
Figure 61.	Coverage Contour Plot of Coverage for U-2 vs. Total Aircraft .....	92
Figure 62.	Coverage by Platform Type.....	93
Figure 63.	Penetrating Scenario: Distribution and Summary Statistics of Mission Area Coverage .....	94
Figure 64.	Penetrating Scenario: Distribution and Summary Statistics of Mission Area Coverage ( <i>single base outliers removed</i> ).....	95
Figure 65.	Actual by Predicted Coverage Plot for Full Quadratic Model.....	96
Figure 66.	Full Quadratic Coverage Model Terms .....	97
Figure 67.	Residual by Predicted Plot for Coverage Model.....	98
Figure 68.	Histogram and Normal Quantile Plot of Residuals for the Coverage Model ..	98
Figure 69.	R-Squared vs. Number of Regression Tree Splits .....	99
Figure 70.	Regression Tree for Coverage .....	101
Figure 71.	Coverage Contour Plot for U-2 vs. Total Aircraft .....	102
Figure 72.	Coverage Contour Plot for RQ-4 vs. Total Aircraft .....	102
Figure 73.	Coverage Contour Plot for RC-135 vs. Total Aircraft.....	103
Figure 74.	Coverage Contour Plot for P-3 vs. Total Aircraft.....	103
Figure 75.	Coverage Contour Plot for RQ-1 vs. Total Aircraft .....	104
Figure 76.	Coverage by Platform Type .....	105
Figure 77.	Proportional Attrition of ISR Platforms.....	106
Figure 78.	Penetrating vs. Non-Penetrating Coverage .....	107
Figure 79.	Non-Penetrating vs. Penetrating Coverage by Platform Type.....	108

Figure 80.	Bivariate Fit of Coverage by Optimization Interval for the Non-Penetrating and Penetrating Scenarios.....	109
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## LIST OF TABLES

Table 1.	Targets and Required Sensors for Collection .....	33
Table 2.	Surface-to-Air Missile Parameters.....	34
Table 3.	ISR Platform Performance Parameters .....	39
Table 4.	ISR Platform Sensor Ranges.....	42
Table 5.	Factors: Assets Assigned to Bases.....	49
Table 6.	Factor: Optimization Interval.....	49
Table 7.	Non-Penetrating Scenario Summary of Base to Mission Area Distance Statistics (The additional transit required due to waypoint routing to prevent COI overflight is included in the distance calculations for this table). ....	67
Table 8.	Non-Penetrating Scenario: Number of Missions Potentially Satisfied from Each Mission Area by Platform and Sensor Type .....	70
Table 9.	Non-Penetrating Scenario: Ability to Satisfy Sensor Requirements by Platform Type (Cells highlighted in red indicate that the sensor requirement cannot be met by any platform type).....	72
Table 10.	Penetrating Scenario Summary of Base to Mission Area Distance Statistics .....	74
Table 11.	Penetrating Scenario: Number of Missions Potentially Satisfied from Each Mission Area by Platform and Sensor Type .....	77
Table 12.	Penetrating Scenario: Ability to Satisfy Sensor Requirements by Platform Type (Cells highlighted in red indicate that the sensor requirement cannot be met by any platform type).....	80
Table 13.	Non-Penetrating Scenario: Low Outlying Data Points.....	82
Table 14.	Penetrating Scenario: Low Outlying Data Points .....	95
Table 15.	Penetrating Scenario: High Outlying Data Points .....	95
Table 16.	JDAFS Bugs Identified and Corrected .....	113

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## EXECUTIVE SUMMARY

A well coordinated and synchronized Intelligence, Surveillance, and Reconnaissance (ISR) program is essential to maintaining global situational awareness and when necessary enabling a response with decisive force. The platforms that conduct ISR missions are a diverse collection of low density, high demand assets with complex operating requirements. These aircraft must be operated in a variety of environments and are subject to limitations in effective range and deployment locations. To further complicate matters, the ability of sensors to collect on intelligence targets of interest is not unlimited. When the targets are beyond the range of the collection platforms and sensors, it is necessary to penetrate the airspace of sovereign nations to gather the required intelligence. This is typically only done during a state of conflict and inherently brings considerable risks. This research develops a Joint ISR scenario, explores scenario simulation results, and provides a proof-of-principle analysis that aids in the ISR decision making process to give the responsive edge to Combatant Commanders.

The U.S. Army Training and Doctrine Command (TRADOC) Analysis Center's Joint Dynamic Allocation of Fires and Sensors (JDAFS) model, a low-resolution, Discrete Event Simulation Model with embedded optimization enables the analysis of many scenarios and factors. This thesis identifies critical JDAFS improvements for the representation of these Joint missions and explores the effects of 21 factors on the Measures of Effectiveness provide by the model. This research examines:

1. What are the trade-offs associated with penetrating versus non-penetrating ISR missions?
2. What are the marginal effects of increasing or decreasing airborne assets within a scenario?
3. What are the appropriate design of experiment (DOE) methodologies and tools for penetrating versus non-penetrating ISR mission analysis?
4. What are the improvements to the JDAFS simulation needed to credibly represent the Joint ISR mission?

JDAFS is a powerful model that combines both discrete event simulation and the optimization of a linear objective function to generate realistic, reasonable, and consistent

solutions to difficult ISR scheduling problems. Given a scenario and a mix of ISR platforms, JDAFS optimizes a flight schedule and executes the missions. JDAFS considers the airframe operational parameters, sensor payload capabilities, base and mission area locations, and line-of-sight inputs in the solution to the ISR scheduling problem.

The scenarios built for this study are designed to conduct a trade-off analysis for Joint ISR operations. Two types of scenarios were generated for examination and comparison within JDAFS. The first scenario is a non-penetrating scenario where the ISR platforms do not penetrate the Country of Interest's (COI) national airspace. The internationally accepted buffer of 22 kilometers is respected on all flights and waypoints have been implemented to prevent ingressing and egressing aircraft from violating the COI's sovereign airspace. The second scenario assumes that conditions have changed to allow the violation of the COI's airspace. With the incursions into the COI's territory comes the risk of engagement by air defense assets, in this case surface-to-air missiles (SAMs). Figure 1 illustrates the penetrating scenario designed for this experiment. The only difference between the penetrating scenario and the non-penetrating scenario is the inclusion of mission areas within the border of the COI for the penetrating scenario.

The country of interest for the scenario is depicted as a hexagon measuring 1000km between any of its widest points. The size of the country allows the missions (ISR targets) to be widely dispersed and ensures that even the most capable sensors included in the study do not cover excessive portions of the country from a single mission area. The missions are dispersed non-uniformly throughout the country to achieve a sense of realism. While the mission dispersal is not uniform, it is also not random. Care is taken to place the missions such that the various mission sensor requirements are widely distributed to limit disproportionate coverage by a single platform. Mission areas were initially designed to ring the entire COI; however, allowing complete access to all countries surrounding a COI may be unrealistic. Overflight of mission areas along the western border and a portion of the southern border were deemed to be denied. Four

operating bases for the ISR platforms were placed at varying distances in the non-denied areas surrounding the COI to allow for different transit times from base to mission area. The air defense sites were distributed throughout the COI.

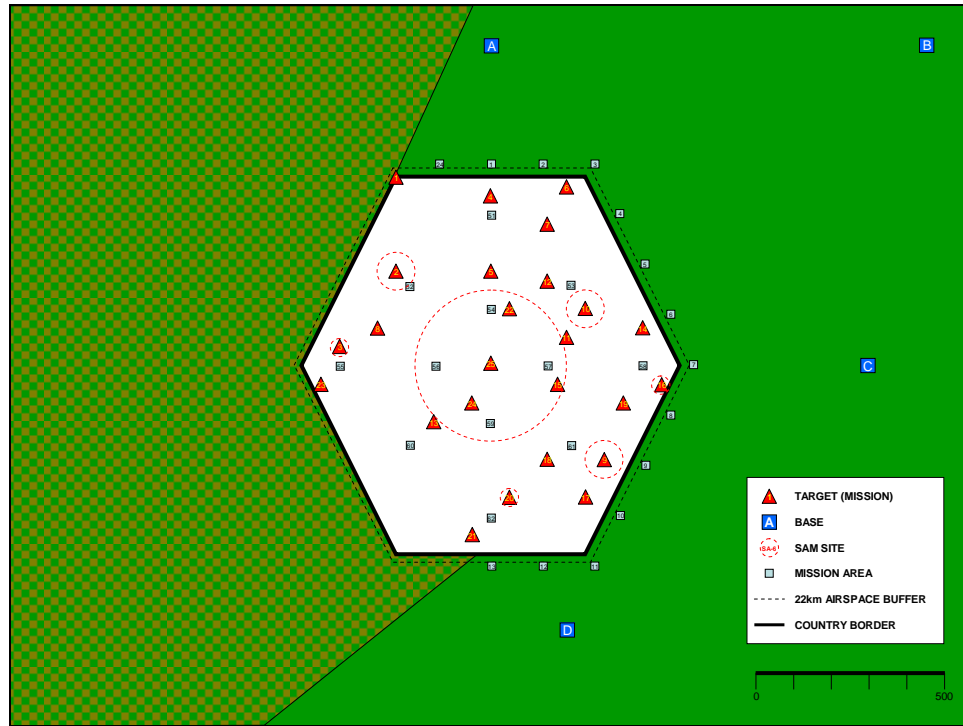


Figure 1. JDAFS Scenario

This study implements an experimental design technique known as the Nearly Orthogonal Latin Hypercube (NOLH) to explore how changes in the input parameters (factors) affect the model output. The 21 factors to be varied in this experiment consist of 20 numbers of aircraft at a base, and 1 optimization interval factor. The 20 aircraft factors take on integer values between 0 and 3 or 0 and 6, depending on the type of airframe. The optimization interval factor is a continuous variable with values between 0.5 and 6 hours.

The NOLH design provides a number of highly desirable qualities, including space filling, orthogonality, and flexibility. Space filling designs provide a means to explore the interior and exterior regions of the response surface, allowing a thorough examination of the output data without the need to run every conceivable design point.



Orthogonality ensures independence of the regressors, or coefficient estimates in resultant regression models. The NOLH design is also flexible, allowing rapid changes to input factors, factor levels, and the size of the overall design space. A sophisticated NOLH design template was used in the creation of the experimental design for this research.

The final design for this experiment includes 274 design points to explore two scenarios; a non-penetrating scenario that allows only standoff collection and a penetrating scenario that allows country of interest overflight. The ISR platforms are subject to attrition by air defense assets in the penetrating scenario but not in the non-penetrating scenario. The scenarios each include 25 collection targets broken down into 55 individual sensor requirements. An analysis of the output data from the two scenarios executed by the JDAFS model suggest:

- Optimization is the most significant factor in both the scenarios, but has the opposite effect. In the non-penetrating scenario, shorter optimization intervals are better, but in the penetrating scenario longer optimization intervals yield improved coverage. Increased assignment options in the penetrating scenario causes this disparate behavior by the optimization interval factor.
- Coverage is not necessarily improved by adding more ISR assets in the non-penetrating scenario.
- Coverage is improved by the addition of assets in the penetrating scenario. Coverage would likely eventually plateau with diminishing returns from the addition of more aircraft in this scenario. The maximum number of airframes in the scenario was not sufficient to explore this behavior.
- Penetrating ISR platforms average 20% more mean coverage than non-penetrating platforms.
- The U-2 is the most important platform factor in explaining the variability in both scenarios.
- The RQ-4 results in the majority of mission coverage for both scenarios due to its ability to remain on station.

**NOTE:** *The ISR platforms and sensors used in this study and their operational parameters and capabilities DO NOT represent actual classified real world performance characteristics.*

In addition to exploring the output from the simulation, JDAFS was exercised to evaluate additional changes that would be required to better model Joint ISR missions. Several recommended additions or improvements were identified:

- Allow ISR platforms to receive credit for collection on targets within sensor range during ingress and egress to mission areas.
- Create probability distributions to represent current and future force sensors from certified data to accurately represent the acquisition of targets by sensors in the model.
- Implement revisit valuation schemes for missions to more credibly represent ISR mission characteristics.
- Addition of joint assets (platforms, sensors, munitions, etc.) in the JDAFS database for reuse in joint studies.
- Further develop the functionality of JDAFS to more credibly represent Joint Sensors to include satellite assets.
- Provide a more robust representation of unmanned aerial vehicles with weapons and sensors that allow force-on-force analysis of differing platform mixes.
- Develop an integrated design of experiments interface that enables a quick determination of alternatives.
- Incorporate the InputGenerator and OutputGenerator scripts into the JDAFS program. The integration of these tools will eliminate the need for the pre and post-processing of data and eliminate the need to transfer excessively large files.
- Develop a simple, well documented JDAFS interface to allow an analyst to easily enter the data for the various input factors.
- Develop a comprehensive JDAFS Users/Analyst Manual.

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# **I. INTRODUCTION**

## **A. BACKGROUND**

The national security of the United States faces dynamic challenges across the globe. A well coordinated and synchronized Intelligence, Surveillance, and Reconnaissance (ISR) program is essential to maintaining global situational awareness and when necessary enabling a response with decisive force. “We know that if the intelligence cycle lags behind operational and command decision-making windows it is not actionable. Just as a maneuver formation on the ground, at sea or in the air is a warfighting system, so is intelligence. By making ISR the responsibility of a functional Combatant Commander we gain synergy and perspective among warfighting systems” (U.S. Congress 2007, 7). The outcome of this research provides tools that aid in the ISR decision making process for the USSTRATCOM Global Defense Posture and give the responsive edge to Combatant Commanders.

The need to plan and act globally is more important than ever before. Writing on the shift from a regional to a global perspective, General Myers (2003), as Chairman of the Joint Chiefs of Staff, noted that,

We will need global ISR activities for gathering indications and warning data and for otherwise enabling global strike, space operations, certain elements of IO, and integrated missile defense. Moreover, we need global C2 capabilities to enable integrated global missile defense, facilitate global strike, integrate regional operations with global operations, and integrate regional operations in one AOR with those of another. Knitting together various regionally focused ISR activities is unlikely to yield a coherent global perspective. Simply put, we cannot obtain a relevant global perspective without ISR activities that, to some degree, are globally coordinated and directed—a function performed by the Defense Intelligence Agency. The new factor is that, given the low-density/high-demand nature of many of our ISR resources, regional combatant commands are more likely than before to be required to conduct ISR activities in support of global operations.

Reflecting the shift in perspective, Change Two to the Unified Command Plan designated US Strategic Command (USSTRATCOM) as the executive agent for the Global ISR mission.<sup>1</sup> The assignment of the Global ISR mission to USSTRATCOM ensures that a comprehensive, global approach is applied to provide timely, survivable, persistent coverage of key targets or areas of interest.

The challenge of meeting the nation's ISR demands is enormous. The platforms that conduct ISR missions are a diverse collection of low density, high demand assets with complex operating requirements. These aircraft must be operated in a variety of environments and are subject to limitations in effective range and deployment locations. To further complicate matters, the ability of sensors to collect on intelligence targets of interest is not unlimited. When the targets are beyond the range of the collection platforms and sensors, it is necessary to penetrate the airspace of sovereign nations to gather the required intelligence. This is typically only done during a state of conflict and inherently brings considerable risks.

A need exists to evaluate the trade-offs based on various ISR platform capabilities and basing configurations. The Joint Dynamic Allocation of Fires and Sensors (JDAFS) model, a low-resolution, Discrete Event Simulation Model with embedded optimization enables the analysis of many scenarios and factors in a relatively short time period when compared to other simulations (U.S. Army Training and Doctrine Command 2007a).

This research is sponsored by the U.S. Army Training and Doctrine Command (TRADOC) Analysis Center (TRAC), Monterey. Collocated with the Naval Postgraduate School, TRAC-Monterey is focused on research in computer simulation technology and military operations research. "TRAC Monterey is recognized as a premier applied research organization for military modeling, simulation, methodologies, and analysis" (U.S. Army Training and Doctrine Command 2007b).

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<sup>1</sup> President Bush signed Change Two to the Unified Command Plan on Jan. 10, 2003, and tasked USSTRATCOM with four previously unassigned responsibilities: global strike, missile defense integration, Department of Defense Information Operations, and C4ISR (command and control, communications, computers, intelligence, surveillance, and reconnaissance) (U.S. Strategic Command, 2007).

## **B. PURPOSE OF RESEARCH**

The purpose of this research is to simulate, by use of the JDAFS model, the effects of varying key factors associated with the operation and employment of manned and unmanned ISR platforms. The main focus of this research is an analysis of the trade-offs associated with specific platforms and basing decisions on the execution of penetrating vs. non-penetrating missions. The analytical findings provide a foundation for future ISR scheduling and requirements decisions. Additionally, prior to commencing production runs, the JDAFS model will be exercised to identify any problems or deficiencies that would prevent the use of this model for the planned research.

## **C. RESEARCH QUESTIONS**

The flexibility and power of the JDAFS model to simulate dynamic ISR missions offers a number of areas for potential research. This research will explore:

1. What are the trade-offs associated with penetrating versus non-penetrating ISR missions?
2. What are the marginal effects of increasing or decreasing airborne assets with in a scenario?
3. What are the appropriate design of experiment (DOE) methodologies and tools for penetrating versus non-penetrating ISR mission analysis?
4. What are the improvements to the JDAFS simulation needed to credibly represent the Joint ISR mission?

## **D. SCOPE OF RESEARCH**

The Design-of-Experiments (DOE) and JDAFS simulation are developed based on two fictional, yet realistic scenarios using data acquired from unclassified sources. In establishing the DOE, specific factors that contribute to the ISR platform attributes of timely, survivable, and persistent are identified. The identified factors are examined at various ranges within the DOE framework. However, the number of factors involved within a full-factorial design makes examining every combination of inputs impractical.

Therefore, an efficient, robust DOE is employed to examine the response surface. Output from the simulation runs is analyzed to evaluate how the various input factors affect the predetermined Measures-of-Effectiveness (MOE) across the range of scenarios.

## **E. THESIS ORGANIZATION**

Chapter II provides a history and description of the Joint Dynamic Allocation of Fires and Sensors (JDAFS) model. Chapter III is an overview of the scenarios to be executed along with a listing of the various manned and unmanned aircraft and sensors modeled in the simulation. Chapter IV covers the design of experiments to facilitate the running of the JDAFS model. Chapter V details the analysis completed on the model output data. Chapter VI is a summary of findings based on the research conducted and includes recommendations for follow-on study.

## **II. JDAFS MODEL, INPUTS AND METHODOLOGY**

### **A. HISTORY OF THE JDAFS MODEL**

The Dynamic Allocation of Fires and Sensors (DAFS) model was created for TRAC-Monterey in 2002 (Havens 2002). DAFS is a low-resolution, constructive entity-level simulation framework programmed in JAVA and incorporates the functionality of the Simkit simulation toolkit created by Dr. Arnold Buss (2006). The original version of the model provided a low-resolution simulation tool for TRAC-Monterey to explore scenarios for the Army's Future Combat System. JDAFS has undergone substantial revision and expansion by TRAC-Monterey to improve the functionality and usability of the model as an analysis tool. In early 2007, the model name was changed to Joint Dynamic Allocation of Fires and Sensors (JDAFS) in recognition that the model's functionality had expanded beyond use for purely Army studies.

Between its original creation in 2002 and early 2007, DAFS has evolved into two separate models:

- Joint Dynamic Allocation of Fires and Sensors (JDAFS), which consisted primarily of the simulation and visualization portion of the program
- Assignment Scheduling Capability for Unmanned Aerial Vehicles (ASC-U) tool, which retained the scheduling and optimization functionality.

As part of this effort, the two programs have subsequently been recombined in the current version of JDAFS.

### **B. JDAFS ORIGINAL CONFIGURATION**

ASC-U and JDAFS were developed from DAFS but were two separate software development branches. ASC-U provided a robust scheduling capability for manned and unmanned aerial sensor platforms using optimization to make assignments using an approximate dynamic programming approach. ASC-U was deterministic since no stochastic effects were considered by the methodology. DAFS provided a low-resolution approach to force-on-force combat and relied on its optimization capability for fires assignment. DAFS represented the stochastic effects of the fires actions.



## **1. JDAFS Functionality**

JDAFS, in its original configuration, was an entity level simulation that relied on scripted scenarios to execute a simulation. Fires allocation was conducted throughout the scenario via an optimization algorithm based on matching available weapons and firing platforms to targets, dependent on acquisition sensor input. The adjudication of fires was a stochastic process driven by a pre-determined distribution. Once a simulation commenced, the scenario would run to completion as scripted with no ability for dynamic re-tasking.

## **2. Event Graph Methodology**

The DAFS discrete event simulation model is built on the concept of Schruben's (1983) event graph methodology. The event graph approach is uniquely suited to describe and implement the types of movement, sensing, and weapons effects interactions required in a low-resolution simulation. The use of event graph methodology can provide significant advantages over a time stepped approach with respect to model run time.

The foundation of event graph methodology is the event list. Discrete event simulations are run by sequentially executing events on the event list. Buss and Ahner (2006b, 1353) provide the following explanation of the event graph:

An Event Graph consists of nodes and directed arcs. Each node corresponds to an event, or state transition, and each arc corresponds to the scheduling of other events. Each arc can optionally have an associated boolean condition and/or a time delay. Figure 2 shows the fundamental construct for Event Graphs and is interpreted as follows: the occurrence of Event A causes Event B to be scheduled after a time delay of  $t$ , providing condition ( $i$ ) is true (after the state transitions for Event A have been performed). By convention, the time delay  $t$  is indicated toward the tail of the scheduling edge and the edge condition is shown just above the wavy line through the middle of the edge. If there is no time delay, then  $t$  is omitted. Similarly, if Event B is always scheduled following the occurrence of Event A, then the edge condition is omitted, and the edge is called an unconditional edge. Thus, the basic Event Graph paradigm contains only two elements: the event node and the scheduling edge with two options on the edges (time delay and edge condition).

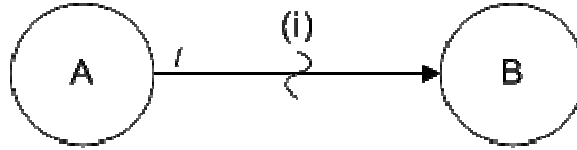


Figure 2. Event Graph Example (From Buss and Ahner 2006b)

For additional information on event graph mythology as it applies to modeling movement and detection, see Simple Movement and Detection in Discrete Event Simulation by Buss and Sanchez (2005).

### C. ASC-U ORIGINAL CONFIGURATION

The scheduling of ISR platforms is an inherently dynamic and complex process. The standalone ASC-U program is a powerful scheduling tool that combines both simulation and optimization to help overcome these complexities. Provided with high quality input data, ASC-U is capable of generating realistic, reasonable, and consistent solutions to difficult ISR scheduling scenarios. (Ahner et al. 2006b, Nannini 2006)

Despite using simulation to determine its solutions, ASC-U is not a stochastic model. It produces identical flight schedules for a given set of input parameters. The simulation portion of the model overcomes the discrete time step artificiality that can be introduced by multi-period optimizations (Ahner et al. 2006a).

While ASC-U is primarily designed for the scheduling of UAV missions, it easily incorporates mixes of manned and unmanned aircraft to solve the following challenge (Ahner et al. 2006a, 2):

Given a scenario that specifies the number of each type of UAV, initial UAV locations, and UAV performance characteristics, determine the number of missions that can successfully be completed and the schedule for each UAV. The solution must consider ground control station (GCS) locations and capacities, launch and recovery site (LRS) locations and capacities...and communication platform footprint and capacities.

The ultimate schedule derived by ASC-U is driven by calculating the maximum total mission value based on the performance parameters of the available ISR platforms.

## **1. Primary ASC-U Components**

ASC-U's primary components consist of missions, ISR platforms, sensor packages, LRSs, GCSs. Each component is populated in a Microsoft Access database using one or more tables for the various elements.

### ***a. Missions***

Missions, or ISR targets, consist of a set of coordinates combined with a set of sensor requirements. For example, a surface-to-air missile site would have a set of locating coordinates and require coverage by electro-optical/infrared (EO/IR) sensors, synthetic aperture radar (SAR), and signals intelligence (SIGINT) sensors. In addition, each sensor requirement is assigned a value rate. ISR platforms receive credit or value by being on-station within sensor range of a sensor requirement provided that the mission, or sensor requirement, is not already being covered by another platform. The total value derived is found by multiplying the value rate of the sensor requirement by the ISR platform's time on-station. ISR platforms that carry multiple sensor packages can fulfill multiple mission requirements. The value achieved by satisfying multiple mission requirements is additive (Ahner et al. 2006b).

### ***b. ISR Platforms***

Individual ISR platforms in ASC-U consist of a unique name, an associated LRS, a transition time, an airspeed, an operational endurance, a GCS operating radius, and one or more sensor types. Unique names automatically generate for the individual ISR platforms to allow mission assignments, the tracking or sensor requirements accomplished, and the state of the platform within the simulation. An ISR platform's airspeed and operational endurance determine feasibility of assignment to specific missions and the amount of time the aircraft can remain on-station prior to returning to an LRS. A platform's transition time accounts for the minimum time an aircraft must spend at an LRS for maintenance and refueling prior to launching for a new mission. The GCS operating radius<sup>2</sup> dictates the maximum distance a UAV ISR platform

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<sup>2</sup> GCS Control Radius was assumed to infinite in this study. All communications with UAVs were deemed to occur via satellite and GCS control is not required for manned platforms.

can travel from a GCS without losing contact. Sensor types assigned to individual platforms determine the types of missions capable of being covered by specific aircraft (Ahner et al. 2006b, 1350).

*c.      **Sensor Packages***

Each ISR platform has an associated sensor package. These packages consist of sensor, weapon, or communications capabilities. These capabilities control the types of missions that are assignable to the various platforms (Ahner et al. 2006b, 1350).

*d.      **LRS***

LRSs provide an operating base from which the ISR platforms operate. An LRS has a unique name, an associated ISR platform type, a set of locating coordinates, and a capacity. While not used within the context of this thesis, LRSs have the ability to move if associated with UAVs (Ahner et al. 2006b, 1350).

*e.      **GCS***

The GCS provides a means for controlling UAV platforms during flight. Like an LRS, a GCS is composed of a unique name, an associated ISR platform type, a set of locating coordinates, and a capacity. Also, just as with LRSs, GCSs have the ability to move during a scenario (Ahner et al. 2006b, 1350).

**2.      Simulation and Optimization**

Using the input data from the components described above, ASC-U uses the combination of optimization and simulation to deliver quality solutions to complex scheduling and assignment problems within an approximate dynamic programming framework. ASC-U is built upon the DAFS discrete event simulation model that contains an embedded constrained value optimizer (CVO).

The CVO algorithm delivers a myopic optimal solution. The myopic, or locally optimal, solution is necessary to maintain problem tractability. The calculation of a globally optimal solution would become computationally infeasible for all but the

smallest of problems. The CVO derives its solution by comparing the ISR resources available to the existing sensor requirements to determine the optimal scheduling to maximize total value (Ahner et al. 2006b, 1351).

### 3. ASC-U Platform Assignment Process

The following description from the ASC-U Users/Analyst Manual illustrates the ASC-U platform assignment process (Ahner et al. 2006a, 4-5):

For example, consider 2 UAVs assigned to 4 missions as depicted in Figure 3. ASC-U performs optimal assignments at predetermined time intervals (1). At time  $t_0$ , assume two UAVs are available, UAV1 and UAV 2. The tool considers all available UAVs with available GCS control and all missions with value in the fixed time horizon time window (missions 1, 2, 3 but not 4 for time  $t_0$ ) (2). A UAV is assigned to a mission and can service any sensor requirement associated with that mission if it has the correct sensor. Assume the optimal assignment is UAV 1 assigned to Mission 1 and UAV 2 assigned to Mission 2. UAV 1 is launched immediately to arrive at Mission 1 as soon as possible (3). UAV 2 does not launch but is scheduled for launch to arrive just-in-time for the beginning of Mission 2. At time  $t_1$ , UAVs that are scheduled to launch but have not yet launched are “unassigned” and considered for assignment (UAV 2 is unassigned) (4). UAV 2 is again assigned to Mission 2 and scheduled for launch to arrive just-in-time. UAV assignments do not change once they have been launched.

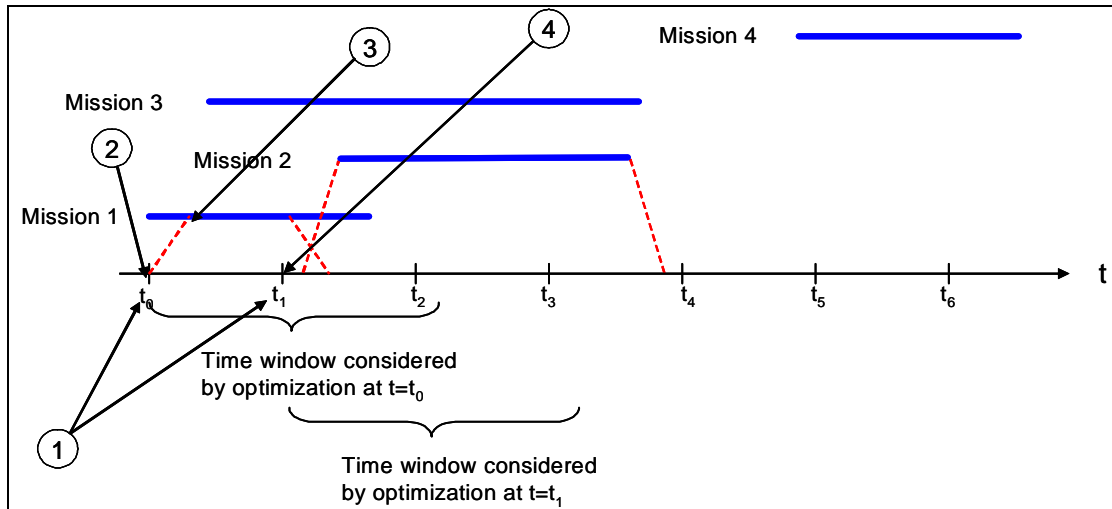


Figure 3. ASC-U Dynamic Cueing and Transitions (From: Ahner et al. 2006a)

The process ASC-U goes through in the construction of flight schedules is illustrated in Figure 4. Beginning in the Dynamic Simulation State Transitions box and proceeding clockwise, the system is prompted to execute an optimization. The Value of Potential Assignment Generator determines the potential value that could be accumulated within the allotted time horizon for all possible ISR platform assignments. The value derived at this stage accounts for all of the parameters affecting the aircraft, including travel time, time-on-station, and GCS capacity. The solution from the Value of Potential Assignment Generator is passed to the optimization routine. The optimization stage returns the locally maximal value of the maximization problem. This solution is passed to the UAV scheduler for platform assignment. The aircraft are slated to launch such that they arrive promptly at the mission start time, taking travel time into account. Following the preset re-optimization time interval the process reenters the Dynamic Simulation State Transition phase and the process continues until a predetermined termination time is met (Ahner et al. 2006a).

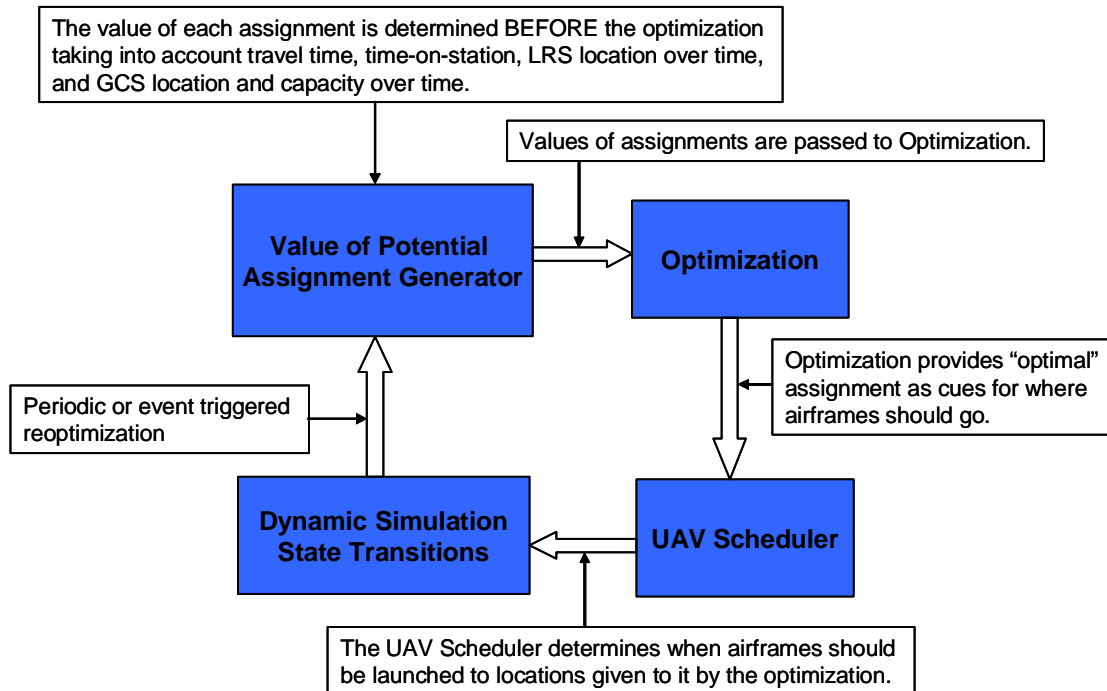


Figure 4. ASC-U Dynamic Cueing and Transitions (From: Ahner et al. 2006a)

For additional details on installing and using the ASU-C tool, see the ASC-U Users/Analysts Manual.

At every optimization event the CVO for the three-dimensional (3D) integer program (IP) must be solved. LP\_Solve 5.5, programmed in C, is implemented in JDAFS and accessed using the Java Native Interface (JNI) (Ahner et al. 2006b, 1351). This solver algorithm is an implementation of the simplex method using the branch and bound technique to solve linear program and integer program formulations. The IP formulation in ASC-U is as follows:

**Indices:**

$i \in MP$	MissionPackage: A package with capabilities that is installed on a MissionPlatform when the MissionPlatform is launched.
$j \in MA$	Mission Area: A location where a MissionPlatform with a MissionPackage patrols.
$k \in Msn$	Mission: A location that requires coverage by a MissionPackage.
$l \in LRS$	LRS: A location that holds MissionPackages and MissionPlatforms that are not currently in use.
$g \in GCS$	GCS: A ground control station.

**Sets:**

$AvailPackage_l$	The set of available MissionPackages at LRS $l$
$Areas_g$	The set of MissionAreas assigned to GCS <sub><math>g</math></sub> (Assignment made by a heuristic prior to optimization)

**Data:**

$ready\_platform_l$	The number of MissionPlatforms ready for launch at LRS <sub><math>l</math></sub> .
$capacity_g$	The remaining GCS capacity at GCS <sub><math>g</math></sub> .
$costToLaunch$	The cost of assigning a MissionPackage to a MissionArea.
$C_{ijk}$	The value gained by assigning MissionPackage $i$ to MissionArea $j$ to cover Mission $k$ .

**Variables:**

$X_{ijk}$	1 if MissionPackage $i$ is assigned to MissionArea $j$ to cover Mission $k$ , 0 otherwise.
$Y_{ij}$	1 if MissionPackage $i$ is assigned to MissionArea $j$ , 0 otherwise.

**Formulation:**

$$1. \quad \text{Max} \sum_{ijk} C_{ijk} * X_{ijk} - \text{costToLaunch} \sum_{ij} Y_{ij}$$

**Subject to:**

2.  $Y_{ij} \leq \sum_k X_{ijk} \quad \forall ij$
3.  $X_{ijk} \leq Y_{ij} \quad \forall ijk$
4.  $\sum_j Y_{ij} \leq 1 \quad \forall i$
5.  $\sum_{ij} X_{ijk} \leq 1 \quad \forall k$
6.  $\sum_{i \in \text{AvailPackage}_l} \sum_j Y_{ij} \leq \text{ready\_platform}_l \quad \forall l$
7.  $\sum_i \sum_{j \in \text{Area}_g} Y_{ij} \leq \text{capacity}_g \quad \forall g$
8.  $X_{ijk} \in (0,1)$
9.  $Y_{ij} \in (0,1)$

**Explanation:**

1. Maximize the total values of the assignments
2. Force  $Y_{ij}$  to be 0 if no Mission is covered by assigning MissionPackage  $i$  to MissionArea  $j$ .
3. Force  $Y_{ij}$  to be 1 if any MissionPackage  $i$  is assigned MissionArea  $j$ .
4. Each MissionPackage is assigned to at most one MissionArea.
5. Each Mission is covered by at most one MissionPackage.
6. The number of MissionPackages from an LRS assigned does not exceed the number of MissionPlatforms ready for launch at the LRS.
7. The number of MissionPackages assigned to MissionAreas covered by each GCS does not exceed the remaining GCS capacity.



8. Ensure that a MissionPlatform is assigned to only one MissionArea at a time.
9. Ensure that a MissionPackage is assigned to only one MissionArea at a time.

**$C_{ijk}$  calculations:**

$C_{ijk}$  will be zero if MissionPackage  $i$  does not have the needed capability to cover Mission  $k$  or Mission  $k$  is not within range or line-of-sight of MissionPackage  $i$  when at MissionArea  $j$ . Otherwise,  $C_{ijk}$  is the total value remaining for Mission  $k$  during the period that MissionPackage  $i$  can be on-station at MissionArea  $j$ , taking into account the endurance of the MissionPlatform carrying the MissionPackage and the ingress/egress time from the LRS at which the MissionPackage is located.

Optimized schedules are ‘flown’ by the simulation portion of the DAFS model in order to capture the dynamics of the platform transitions and movement. The simulation functionality takes on increased importance in scenarios where fires and complex relationships between moving GCSs and LRSs are involved.

## **D. CHANGES IMPLEMENTED IN JDAFS**

To maximize the usefulness of JDAFS as analytical tool, several changes are necessary. These improvements involve restoring some of the capabilities from the original model, as well as, adding new functionality. The following modifications are the initial changes identified to make the simulation viable for this study; further operational testing of JDAFS is necessary to identify any remaining bugs and deficiencies prior to conducting production runs.

### **1. Scheduling Tool**

To simulate an ISR scenario from start to finish, some means of creating a flight schedule or Air Tasking Order (ATO) is required. While several options were considered, including building a fixed schedule prior to execution or the creation of a heuristic scheduling method, the best alternative was to integrate ASC-U back into JDAFS. This created not only the ability to build schedules on the fly, but also the means to optimize the flight schedule as the simulation progressed. In addition, ASC-U, coupled with pre-calculated line-of sight determinations between mission and mission areas solves a two stage assignment problem.

## **2. Mission Areas**

The creation of mission areas was required to provide a method to simulate an ISR platform on-station. As a low-resolution simulation, JDAFS does not model flight characteristics that would be included in a higher resolution model such as turning, climbing, descending, speed changes, and other more sophisticated performance parameters. In JDAFS, platforms actually transit from a base to a mission area and remain stationary at that mission area for the duration of the sortie. This artificiality is a trade-off between functionality in the form of minimizing solution times necessary for the execution of the model and realism.

## **3. Bases**

The integration of ASC-U brings with it the ability to create Launch and Recovery Sites (LRS) and Ground Control Stations (GCS). Virtual operating bases can be established by setting a common set of coordinates for these entities and associating specific ISR platforms. ASC-U has the ability to account for mobile GCSs and LRSs, however, for this study, all GCSs and LRSs with identical coordinates are treated as fixed operating bases.

## **E. IMPROVED JDAFS CONFIGURATION**

The current version of JDAFS is a more robust version of the original program. It incorporates all of the functionalities of the ASC-U program described above along with a richer simulation capability. The remainder of this section addresses specific details related to the description and execution of the improved JDAFS configuration.

### **1. LOS Calculation**

The minimum altitude line-of-sight (LOS) between all missions and mission areas is pre-calculated prior to the execution of any JDAFS scenario. The predetermination of the minimum altitude LOS is what enables 3D optimization in the execution of JDAFS scenarios. For the purposes of this study, minimum altitude (LOS) is calculated in two steps. First, the distance between the mission and mission area is calculated as follows:

$$\text{Distance} = \sqrt{(x_{\text{mission}} - x_{\text{mission area}})^2 + (y_{\text{mission}} - y_{\text{mission area}})^2}$$

Second, the minimum altitude required to achieve LOS is calculated<sup>3</sup>:

$$\text{Minimum Altitude} = \frac{(\text{Distance})^2}{2 \times 6378155}$$

The results of the LOS calculations are then used to populate the MinLOSAlt field in the LOS input table.

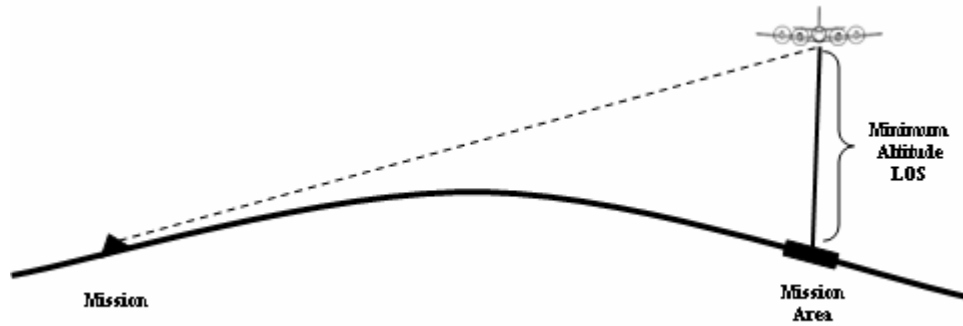


Figure 5. Minimum Altitude Line-of-Sight Determination

The scenarios in this study assume flat terrain with only the curvature of the earth affecting the ability to achieve line-of-sight. The inclusion of manmade or terrestrial terrain features obstructing LOS are beyond the scope of this study. For the execution of JDAFS scenarios based on real world geographic locations, a LOS calculation tool has been created by TRAC-MTRY. The LOS tool uses Digital Terrain Elevation Data (DTED) to calculate the minimum altitude LOS based on the terrain at and around the actual coordinates of the missions and mission areas.

## 2. Input Requirements

JDAFS runs on an XML file created from inputs in an Access database. The Access database contains the various tables required for the execution of a scenario.

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<sup>3</sup> The minimum altitude calculation is derived from the equation for determining the distance to the visual horizon: Distance to the visual horizon  $R = (2 \cdot R_{\text{earth}} \cdot h)^{0.5}$  where h is the sensor height, in meters, and  $R_{\text{earth}}$  is the radius of the earth at the equator, 6378155 meters (Wittenberg 1997).

Only the data tables used for this study will be discussed further. For information on the complete list of tables and their uses see the ASC-U User's/Analyst Manual (Ahner et al. 2006b) and the JDAFS User's Guide (Ahner et al. 2006c).<sup>4, 5</sup>

*a. DAFSScenario*

The DAFS Scenario table is the primary driver for the simulation. Key elements determined in this table include the optimization interval, the number of replications to be executed, and the length of the scenario to be simulated. DAFSScenario elements consist of:

- **Version:** The version of the input file—used to determine the schema of the input.
- **Type:** Currently only 'Attack' is used.
- **optimizeInterval:** Time between optimization events for the CVO.
- **bdaFactor:** A number between 0.0 and 1.0 representing the probability that BDA will be correct (not used).
- **replications:** Number of replications to be done.
- **stopTime:** Length of the scenario.

*b. GCS*

The Ground Control Station (GCS) table indicates the name, the associated LRS, and control capacity of each ground control station. A GCS and its associated LRS constitute an operating base for the launch, control, and recovery of ISR platforms. The GCS table elements are:

- **Name:** A unique identifier for each GCS.
- **LRS:** The name of the LRS associated with the GCS.
- **Capacity:** The maximum number of platforms (i.e., UAVs) that the GCS can control at any one time. Only the first entry for each GCS is used.

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<sup>4</sup> Data table names, letter case and spelling are taken directly from the current version of the JDAFS input tables.

<sup>5</sup> Descriptions of the elements in the data tables are taken from either the ASC-U Users/Analysts Manual or the JDAFS Users Manual as applicable. Where necessary, the wording has been changed to match the current usage in JDAFS.

*c. GCSLocation*

GCS Location is associated with the GCS table to provide the geographic location of the GCS and the time at which it becomes available. For this study the GCSs are available throughout the entire scenario and their location is fixed. The GCSLocation table is comprised of the following elements:

- **GCS:** Name of this GCS from the GCS table.
- **Time:** The H-hour at which this GCS is at the location designated by the LocationX and LocationY elements.
- **LocationX:** The x coordinate of this GCS at the time in the Time element.
- **LocationY:** The y coordinate of this GCS at the time in the Time element.

*d. LinearKillProbability*

The linear kill probability table provides the elements necessary to evaluate the outcome of a firing event. Each munition type is named and must be specifically matched with a target platform vulnerable to attack with the weapon. The minimum and maximum range for the munition type and the respective kill probabilities ( $P_k$ ) are also defined in this table. Elements of the LinearKillProbability table are:

- **munitionType:** The munition for which the kill probability is defined. This must be defined in a MunitionType element.
- **platformType:** The target platform for the LinearKillProbability definition. This must be defined in a PlatformType element.
- **class:** JAVA class that adjudicates the firing action.
- **minRangePK:** The probability of kill against a target platform at minimum range.
- **maxRangePK:** The probability of kill against a target platform at maximum range.
- **minRange:** Minimum range at which a target can be engaged.
- **maxRange:** Maximum range at which a target can be engaged.

*e. LOS*

The line-of-sight (LOS) table provides the necessary data for the two stage assignment problem. The values are pre-calculated to determine the minimum altitude at which there is an unobstructed line of sight between a mission and a mission (target). The elements that make up the LOS table are:

- **Mission:** The name of the mission from the Mission table that corresponds the Mission Area for which the minimum altitude to maintain line-of-sight is designated in the MinLOSAlt element.
- **MissionArea:** The name of the Mission Area from the MissionArea table that corresponds the Mission for which the minimum altitude to maintain line-of-sight is designated in the MinLOSAlt element.
- **MinLOSAlt:** The minimum altitude in meters required to maintain line-of-sight between the Mission Area and the Mission locations.

*f. LRS*

Launch and recovery sites (LRS) are named and the capacity is defined in the LRS table. A LRS and its associated GCS constitute an operating base for the launch, control, and recovery of ISR platforms. The LRS-GCS association is done in the GCS table. The LRS elements consist of:

- **Name:** A unique identifier for each LRS.
- **Capacity:** The maximum number of each ISR platform at the LRS.

*g. LRSLocation*

LRS Location is associated with the LRS table to provide the geographic location of the LRS and the time at which it becomes available. For this study the LRSs are available throughout the entire scenario and their location is fixed. The LRSLocation table is comprised of the following elements:

- **LRS:** The name of the LRS from the LRS table.
- **Time:** The H-hour at which this LRS is at the location designated by the LocationX and LocationY elements.
- **LocationX:** The x coordinate of this LRS at the time in the Time element.
- **LocationY:** The y coordinate of this LRS at the time in the Time element.

#### *h.      MetaData*

The metadata table drives how a design scenario will be run by JDAFS. Most significantly, the MetaData table defines the type of optimization algorithm to be implemented, the length of the simulation scenario, the time between optimizations, and the location of the origin for the scenario coordinate system. Elements in the MetaData table are:

- **InputFormatVersion:** Reports the current version of the input format.
- **CVOType:** Identifies CVO JAVA class to use.
- **ScenarioLength** is the length of the scenario to be run in simulation hours.
- **OptimizationInterval** is the amount of time in simulation hours between reallocation of the ISR platforms.
- **ReportInterval:** Frequency of report intervals (not used).
- **DiscountFactor:** Discount for time into the future (not used).
- **EarlyReturn:** Heuristic (not used).
- **SecondaryAreas:** Heuristic (not used).
- **AppendAreas:** Heuristic (not used).
- **LocationType:** Heuristic (not used).
- **OriginLat:** Sets origin latitude for the scenario.
- **OriginLng:** Sets origin longitude for the scenario.
- **CostToLaunch:** (not used).

#### *i.      Mission*

The targets for collection by the ISR platforms are called missions. Each mission is defined by a name, a location, the type of sensor required to collect on the mission, and the value the correct sensor achieves per hour for coverage of the mission. The Mission table elements consist of:

- **Name:** Unique identifier for each mission (target).
- **LocationX:** The x coordinate of the mission (target).
- **LocationY:** The y coordinate of the mission (target).
- **StartTime:** The time that the sensor requirement starts, usually in H-hours (not used).

- **EndTime:** The time that the sensor requirement ends, usually in H-hours (not used).
- **RequiredCapability:** The sensor type required to detect this mission.
- **ValueRate:** The rate at which an ISR platform with the correct sensor receives credit when the mission (target) is in the ISR platform's sensor footprint (all values assigned as 1.0 for this study).

*j. MissionArea*

A mission area is a notional on-station location for the ISR platforms consisting of a name and a location. The elements in the MissionArea data table are:

- **Name:** Unique identifier for each mission area (patrol location).
- **LocationX:** The x coordinate of the mission area (patrol location).
- **LocationY:** The y coordinate of the mission area (patrol location).

*k. MissionPackageLocation*

The mission package location indicates how many of the mission packages, defined in the MissionPackageType table, are located at each LRS (base). A new row is required for each mission package at a LRS. The MissionPackageLocation attributes are:

- **LRS:** Unique identifier for the Launch and Recovery Site at which the MissionPackageType (ISR platform) is located. Each LRS can only be associated with one MissionPackageType (ISR Platform). Multiple LRSs can be associated with a single geographic location in the MissionPlatformLocation table using the UnitName element.
- **MissionPackageType:** Name of the ISR platform associated with the LRS.
- **QTY:** Number of MissionPacakgeTypes at the LRS.

*l. MissionPackageType*

The mission package type defines the sensor packages that ISR platforms may carry. Each package has a unique number followed by unique names of sensors that together make up the package. Each row of the MissionPackageType table represents one sensor package. The MissionPackageType elements are:



- **Name:** Unique name of an ISR platform.
- **CapabilityType:** Type of sensor payload associated with the ISR platform in the Name element. If the ISR has more than one sensor payload, each sensor must be listed individually with the corresponding Name element.

*m. MissionPlatformLocation*

Each row of the mission platform location table defines the number of ISR platforms of a particular type assigned to a LRS (base). The MissionPlatformLocation elements are:

- **LRS:** Unique identifier for the Launch and Recovery Site at which the MissionPackageTypes (ISR platform) are located. Each LRS can only be associated with one MissionPackageType (ISR Platform). Multiple LRSs can be associated with a single geographic location by using the UnitName element.
- **UnitName:** Unique name for a unit (base, airfield, or launch platform) which can be associated with multiple LRSs.
- **PlatformType:** Type of ISR platform at an LRS associated with a specific unit (base, airfield, or launch platform).
- **Qty:** Number of MissionPlatformTypes at the MissionPlatformLocation (unit).
- **StartAvailable:** The time that the mission platform becomes available, usually in H-hours.
- **EndAvailable:** The time that the mission platform is no longer available, usually in H-hours.

*n. MissionPlatformType*

The mission platform type table contains all the performance characteristics for the ISR platforms. The elements of the MissionPlatformType are:

- **Name:** The name of an individual type of ISR platform.
- **TransitionTime:** The amount of time, in hours, between the recovery of a platform and the time that it is available for a new mission.
- **AirSpeed:** The rate of travel of the ISR platform in meters per hour.
- **ControlRadius:** The maximum distance a platform requiring a Ground Control Station can be from a controlling CGS for effective control (Assumed to be via SATCOM and not used).

- **OperationalEnd:** The maximum time a platform can be away from an LRS, the platform's endurance.
- **TimeHorizon:** The time used for the optimization. Time horizon is usually 1 to 1.5 times the operating time. This value may need to be adjusted if transition time is greater than half the operating time. This value is critical to determining what missions will be considered in the look-ahead time window to launch a UAV if GCS capacity is available.
- **MaxAltitude:** Maximum operational altitude of the platform in meters.

*o. Mover*

The mover table enables the creation of different types of platforms. In this case only red or threat platforms (SAMs) are created. The mover platforms are assigned a name, a type (i.e., SAM), CVO type and an affiliation. Multiple copies of identical platforms can be created, if required. Note that ISR platform creation is done in a separate process in another table. The specific elements in the Mover table are:

- **name:** An identifier given to track agents within the simulation. If multiple platforms are created, they are given unique numbers in addition to the name.
- **type:** The fully qualified name of the implanting Mover class. This must be specified in the PLATFORM table of the database.
- **qty:** The number of identical platform that will be created. Defaults to 0.
- **assignment:** specifies whether the platform will be controlled by a fires CVO("fires"), a sensor CVO("sensor"), both("both") or none ("none").
- **affiliation:** "Red" or "Blue" as listed in the SIDE table of the database (required).
- **xLoc:** The initial x coordinate of the agent unless a Box is used. If a Box is used, enter 0 as the initial x coordinate.
- **yLoc:** The initial y coordinate of the agent unless a Box is used. If a Box is used, enter 0 as the initial y coordinate.
- **MaxSpeed:** The maximum platform speed in meters per hour (not used).
- **OperationalEndurance:** The maximum operational endurance of the platform in hours (not used).
- **formationLeader:** Defines the lead platform when movers travel in formation (not used).

*p. MoverManager*

The mover manager controls the movement of mover platforms when they are not given assignments from a CVO. This table must be completed for each mover even if none of the movers defined will actually travel. In this study, all of the mover platforms are fixed and do not move. The MoverManager attributes are:

- **ID:** An automatically generated number to track the different agents.
- **class:** The fully qualified name of the MoverManager class. The typical values are:
  - DAFS.platform.DAFSPathMoverManager
  - DAFS.platform.DAFSPatrolMoverManager
  - DAFS.platform.NAIMoverManager
- **mover:** The unique name given to the agent from the MOVE table.
- **delay:** Optional double value (must be  $\geq 0.0$ ). Specifies the time after 0.0 that the MoverManager will become active. If omitted, then an explicit call to start() is required to activate the MoverManager.
- **startOnReset:** Optional Boolean (“true” or “false”); if “true”, the specified MoverManager will commence its operation at the start of the simulation without any explicit command. If “false” or omitted, an explicit call to start() is required for the MoverManager to become active.

*q. Munition*

Munition is the definition for a weapon type consisting of a unique identification number, a noun name, and a mover assignment. The mover assignment determines the firing platform for the weapon. The operational parameters for the munition are characterized in the MunitionType table. The Munition elements are:

- **ID:** Automatically generated identification number for the individual munitions.
- **Type:** Name of the munition type.
- **mover:** Name of the mover (TEL, prime mover, aircraft, etc.) upon which the munition is loaded.

*r. MunitionType*

The munition type table provides the parameters for an individual munition defined in the Munition table. Key attributes for the munition type are the maximum effective blast radius, the minimum and maximum effective ranges, and speed. The columns in the MunitionType table are:

- **MUNITION:** A unique name for the ordinance.
- **WEIGHT:** Weight in pounds of the weapon (not used).
- **MER:** Effective blast radius in meters (minimum is 1.0).
- **MINRANGE:** Minimum range in meters.
- **MAXRANGE:** Maximum range in meters.
- **LOAD:** The number of rounds included in a basic load out (initial quantity per platform).
- **SPEED:** The speed of the round in meters per hour.
- **ALGORITHM:** Determines what algorithm should be used dependent on type of munition.
- **BURST\_SIZE:** For indirect fires, defines the effects radius from impact (not used).
- **SUBMUNITION:** Allows for submunitions and their effects (not used).

*s. PlatformType*

All non-ISR platform entities that are not mover entities in a scenario must be defined in the platform type table. SAM is the only PlatformType used in this study. The PlatformType elements are:

- **name:** Link to mover.
- **value:** Value used in fires CVO, set to zero and not used in this experiment.

*t. Route*

The route table provides a method for controlling the flight path of an ISR platform during travel between its home base (LRS/GCS) and the assigned mission area. Each entry in the table contains a single enumerated waypoint. Multiple entries are

required when more than one waypoint is necessary. If no routing is defined, the aircraft travel in a shortest path straight line between the base and the mission area. The Route elements are:

- **StartLocation:** Name of the LRS at which the mission originates.
- **MissionArea:** Name of the destination Mission Area for the route.
- **PointNumber:** Number indicating the sequence of the waypoint in the route.
- **LocationX:** The x coordinate of the waypoint.
- **LocationY:** The y coordinate of the waypoint.

*u. Sensor*

The sensor table creates a relationship between a mover and a sensor type for the sensors defined in the SensorType table. There is no relationship between the Sensor table and SensorRange table. The types of sensor relationships created in this study are strictly for red or threat platforms. The Sensor elements are:

- **ID:** AutoNumber used to track the sensors.
- **type:** As described under the SensorType Table.
- **mover:** The agent the sensor is assigned to.

*v. SensorRange*

Sensor range provides the maximum sensor range for the sensors to be carried by the ISR platforms. The types of sensors defined in this table consist of three elements, the platform type to carry the sensor, the sensor capability type, and the sensor range. This allows the creation of sensors of similar types with different ranges. For example, the EO sensor carried by a U-2 can have a different range than an EO sensor mounted on a RQ-1. There is no relationship between the SensorRange table and Sensor or Sensor type tables. The sensors created in this table are strictly for blue platforms. Columns in the SensorRange table consist of:

- **MissionPlatformType:** Name of the platform that carries the sensor.
- **MissionCapabilityType:** Type of coverage provided by the sensor. The three capability types defined are EO/IR, SAR, and SIGINT.
- **Range:** Maximum range of the sensor in meters.

w. *SensorType*

Sensor type creates a name and range for sensors that can be mounted on mover platforms. For this study, the SensorType table is used to create notional SAM fire control radars. There is no relationship between the SensorType table and SensorRange table. The SensorType elements are:

- **name:** A unique name for the sensor.
- **maxRange:** The maximum range of the sensor in meters.
- **class:** The fully qualified class name for the sensor.

x. *Side*

Side determines the affiliation of the entities in the simulation (i.e., red or blue). The side table contains only one element:

- **name:** Designates affiliation. Red indicates enemy and blue indicates own forces.

y. *SimEntity*

The SimEntity element is where platforms are defined. Each platform is defined in a Mover sub-element.

- **elements:** The SimEntity has no attributes.

### 3. Execution

Simulation runs in JDAFS can be executed in a number of ways. Single runs, including multiple replications of the same scenario, can be made using either the JDAFS Graphical User Interface (GUI) (See Figure 6), or the command line. The implementation of more complex experiments requiring multiple replications of many design points should be run from a computing cluster.

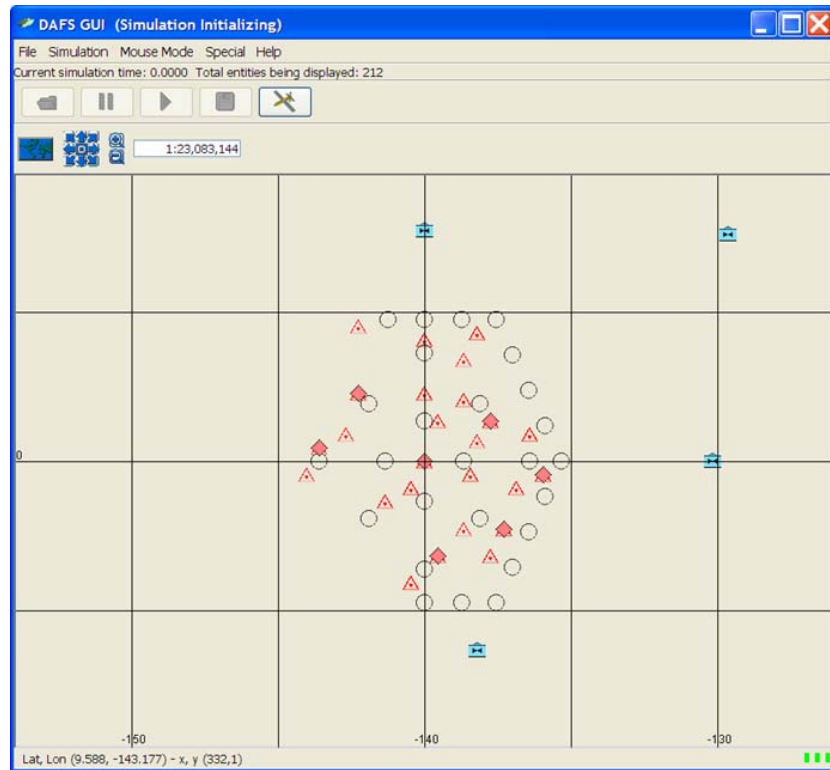


Figure 6. JDAFS Graphical User Interface

#### 4. Output

Upon completion of each simulation, output tables are generated or populated depending on the method used to run the scenario. Single runs from the JDAFS GUI produce new Microsoft Access databases that must be manually saved following the completion of the simulation. Output from command line or computing cluster runs are saved back to output data tables in the original input database.

JDAFS has the ability to create multiple output tables to capture MOE and model run parameters. These output tables include: Acquisition, Coverage, Coverage by Type, Coverage Delay, Killer-Victim Scoreboard, Mission Assignment, Run Information, and Schedule. Only the output tables capturing the MOEs of interest (Coverage, Coverage by Type, and Killer-Victim Scoreboard) for this research will be described in detail. For an

explanation of the other tables, see the ASC-U Users/Analyst Manual (Ahner et al. 2006b) The following data tables and their associated elements are created at the completion of each run:<sup>6,7</sup>

*a. Coverage*

The Coverage table contains one row for each Mission in the scenario. The elements in the Coverage table are:

- **Replication:** Number indicating the simulation run which provided the data.
- **Mission:** The name of the Mission. For this study, the mission name is a numerical code where the number before the decimal represents the mission name and the number after the decimal identifies the type of sensor required to cover the mission.
- **Open Time:** The total time, in hours, that the mission was vulnerable to coverage by the required sensor.
- **Covered Time:** The total amount of time, in hours that the mission was covered by the required sensor.
- **Coverage:** The percentage of time that the mission was covered by at least one sensor during the replication.
- **Value Rate:** The value received per unit time by the covering platform.
- **Total Value:** The total value obtained from this Mission during the scenario.

*b. Coverage by Type*

The Coverage by Type table contains one row for each Mission/ISR platform type. The following columns make up the Coverage by Type table:

- **Replication:** Number indicating the simulation run which provided the data.
- **Mission:** The name of the Mission. For this study, the mission name is a numerical code where the number before the decimal represents the mission name and the number after the decimal identifies the type of sensor required to cover the mission.

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<sup>6</sup> Data table names, letter case and spelling are taken directly from the current version of the JDAFS input tables.

<sup>7</sup> Descriptions of the elements in the data tables are taken from the ASC-U Users/Analysts Manual. Where necessary, the wording has been updated to match the current usage in JDAFS.



- **Mission Platform Type:** The type of platform assigned to the Mission.
- **Open Time:** The total time, in hours, that the mission was vulnerable to coverage by the required sensor.
- **Covered Time:** The total amount of time, in hours that the mission was covered by the required sensor.
- **Coverage:** The percentage of time that the mission was covered by at least one sensor during the replication.
- **Value Rate:** The value received per unit time by the covering platform.
- **Total Value:** The total value obtained from this Mission during the scenario.

*c. KillerVictimScoreboard*

The Killer-Victim Scoreboard provides a means of measuring attrition for a scenario. Each row in the table gives details on individual engagements. The Killer-Victim Scoreboard is composed of the following columns:

- **Replication:** Number indicating the simulation run that provided the data.
- **Sim Time:** Time in the simulation that the firing event occurred.
- **Firing Platform:** Name of the platform that launched the weapon.
- **Munition:** Type of munition fired by the platform.
- **launch x:** The x coordinate of the firing platform at the time of the firing event.
- **launch y:** The y coordinate of the firing platform at the time of the firing event.
- **weight:** Weight of the munition (not used).
- **Target:** The unique name of the platform targeted.
- **target x:** The x coordinate of the target at the time of the firing event.
- **target y:** The y coordinate of the target at the time of the firing event.
- **type:** Type of platform targeted.
- **target value:** Value of the target (not used).
- **target side:** Affiliation of the target platform.
- **outcome:** Result of the engagement, missed or killed.

### **III. SCENARIO DEVELOPMENT**

#### **A. SCENARIOS**

The scenarios<sup>8</sup> built for this study are designed to conduct a trade-off analysis for Joint ISR operations. Two types of scenarios were generated for examination and comparison within JDAFS. The first scenario is a non-penetrating scenario (See Figures 7 and 8, p. 35) where the ISR platforms do not penetrate the Country of Interest's (COI) national airspace. The internationally accepted buffer of 22 kilometers is respected on all flights and waypoints have been implemented to prevent ingressing and egressing aircraft from violating the COI's sovereign airspace. The second scenario (See Figures 9 and 10, p. 36) assumes that conditions have changed to allow the violation of the COI's airspace. With the incursions into the COI's territory comes the risk of engagement by air defense assets, in this case surface-to-air missiles (SAMs).

The country of interest for the scenario is depicted as a hexagon measuring 1000km between any of its widest points. The size of the country allows the missions (ISR targets) to be widely dispersed and ensures that even the most capable sensors included in the study do not cover excessive portions of the country from a single mission area. The missions are dispersed non-uniformly throughout the country to achieve a sense of realism. While the mission dispersal is not uniform, it is also not random. Care is taken to place the missions such that the various mission sensor requirements are widely distributed to limit disproportionate coverage by a single platform. Mission areas were initially designed to ring the entire COI; however, allowing complete access to all countries surrounding a COI may be unrealistic. Overflight of mission areas along the western border and a portion of the southern border were deemed to be denied. Four operating bases for the ISR platforms were placed at varying distances in the non-denied areas surrounding the COI to allow for different transit times from base to mission area. The SAM sites were distributed across the COI with the strategic SAMs (SA-2 and SA-

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<sup>8</sup> There is no intention to depict any real world operational area or threat order of battle.

10) treated as missions. The tactical SAMs (SA-6) were placed as point defense weapons at three separate mission types. See Figures 7, 8, 9, and 10 (pp. 35 and 36) for the specific placement of entities in this scenario.

The design of a scenario for use in exercising the JDAFS model requires the creation of the following components:

### **1. Missions (Targets)**

For the purposes of this simulation, 25 missions or targets of varying types were created and populated throughout the COI (See Figures 7, 8, 9 and 10, pages 35 and 36). Target types consist of command and control (C2) nodes, surface-to-air missiles (SAMs), short range ballistic missiles (SRBMs), medium range ballistic missiles (MRBM), long range ballistic missiles (LRBMs), airfields, weapons of mass destruction facilities (WMD FACs), military facilities (MIL FACs), and ammunition storage (AMMO STOR) facilities. Intelligence information for each type of target can only be collected against by specific types of sensors. The mission/sensor interactions must be explicitly created in the input tables and result in the creation of 55 target elements from the 25 actual missions (targets). The missions and their sensor requirements are listed in Table 1.

MISSION	TYPE	EO/IR	SAR	SIGINT
1	C2			X
2	SA-2	X	X	X
3	WMD FAC	X		
4	IRBM	X	X	X
5	AIRFIELD	X	X	X
6	SRBM	X	X	X
7	C2			X
8	C2			X
9	SA-2	X	X	X
10	SA-2	X	X	X
11	C2			X
12	AMMO STOR	X	X	
13	AMMO STOR	X	X	
14	IRBM	X	X	X
15	LRBM	X	X	X
16	SRBM	X	X	X
17	MIL FAC	X	X	
18	WMD FAC	X		
19	MIL FAC	X	X	
20	MIL FAC	X	X	
21	IRBM	X	X	X
22	MIL FAC	X	X	
23	C2			X
24	AIRFIELD	X	X	X
25	SA-10	X	X	X

Table 1. Targets and Required Sensors for Collection

## 2. Mission Areas

Mission areas (See Figures 7, 8, 9 and 10, pp. 35 and 36) are the locations created to simulate on-stations positions for the ISR platforms. The non-penetrating scenario has 14 mission areas positioned outside the COI and the penetrating adds an additional 12 mission areas inside the COI. The 14 non-penetrating mission areas are what remain of an originally plotted 24 mission areas after deleting the points deemed to be inaccessible due to being in a country that has denied overflight rights. For the placement of the 12 additional penetrating mission areas, no regard was given to minimum risk flight routing in order to enable the examination of the effects of attrition.

### 3. Bases

Four airfields or bases (See Figures 7, 8, 9 and 10, pp. 35 and 36) were created by assigning fixed common sets of coordinates to GCSs and LRSs. ISR platforms are then associated with specific GCSs and LRSs to establish the asset lay down at each base. The four bases are varying distances from the COI to take into account the differences in transit times that would be expected in real world operations.

### 4. Threats

The threats depicted in this scenario (See Figures 7, 8, 9 and 10, pp. 35 and 36) are all surface-to-air missiles (SAMs). Three different SAM systems of varying ranges were selected for inclusion in the scenario: the SA-2, SA-6, and SA-10. The  $P_k$  for the SAMs was assumed to be the same against all ISR platforms. Studies conducted with real world operational data and parameters would have a separate  $P_k$  for each individual ISR platform. The SA-6, a mobile platform, is used in fixed positions for this scenario. The SA-6s are not treated as missions or targets for this study, but are all collocated with missions.

The operational parameters for the threat platforms used in JDAFS for this thesis are listed in Table 2. For real world studies conducted in a classified environment, operational parameters would be provided by the organization sponsoring the research.

THREAT	MIN RANGE (meters)	MAX RANGE (meters)	MIN RANGE $P_k$	MAX RANGE $P_k$
SA-2	1000	50000	0.6	0.5
SA-6	1000	24000	0.6	0.5
SA-10	1000	200000	0.6	0.5

Table 2. Surface-to-Air Missile Parameters

While not used in this scenario, other types of threat platforms can also be depicted in JDAFS such as, Anti-Aircraft Artillery (AAA) and fighter/interceptor aircraft.

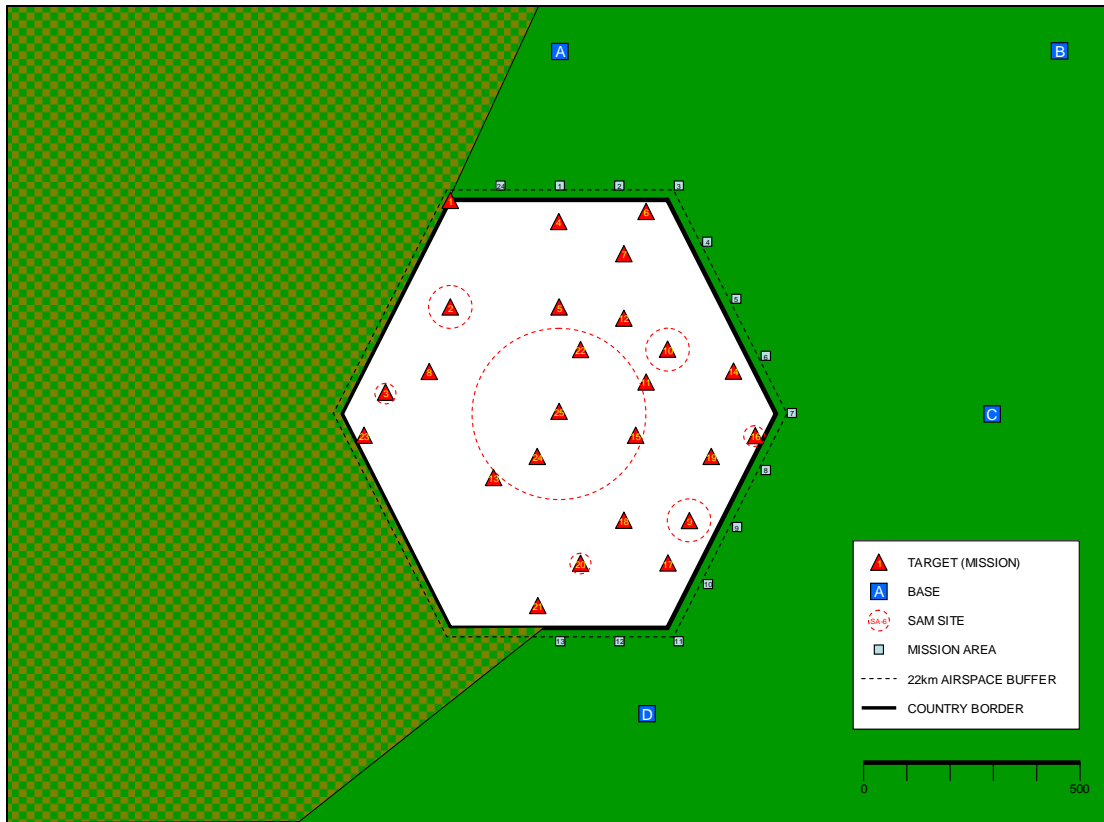


Figure 7. JDAFS Non-Penetrating Scenario as Designed (*Best viewed in color*)

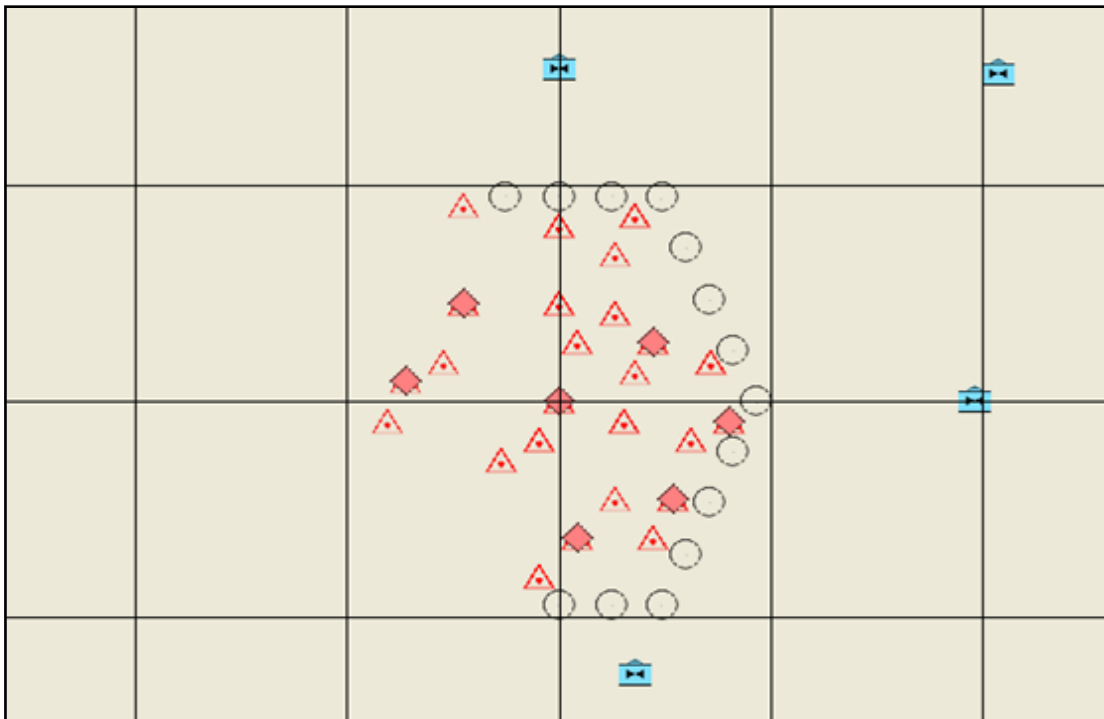


Figure 8. JDAFS Non-Penetrating Scenario in JDAFS GUI (*Best viewed in color*)

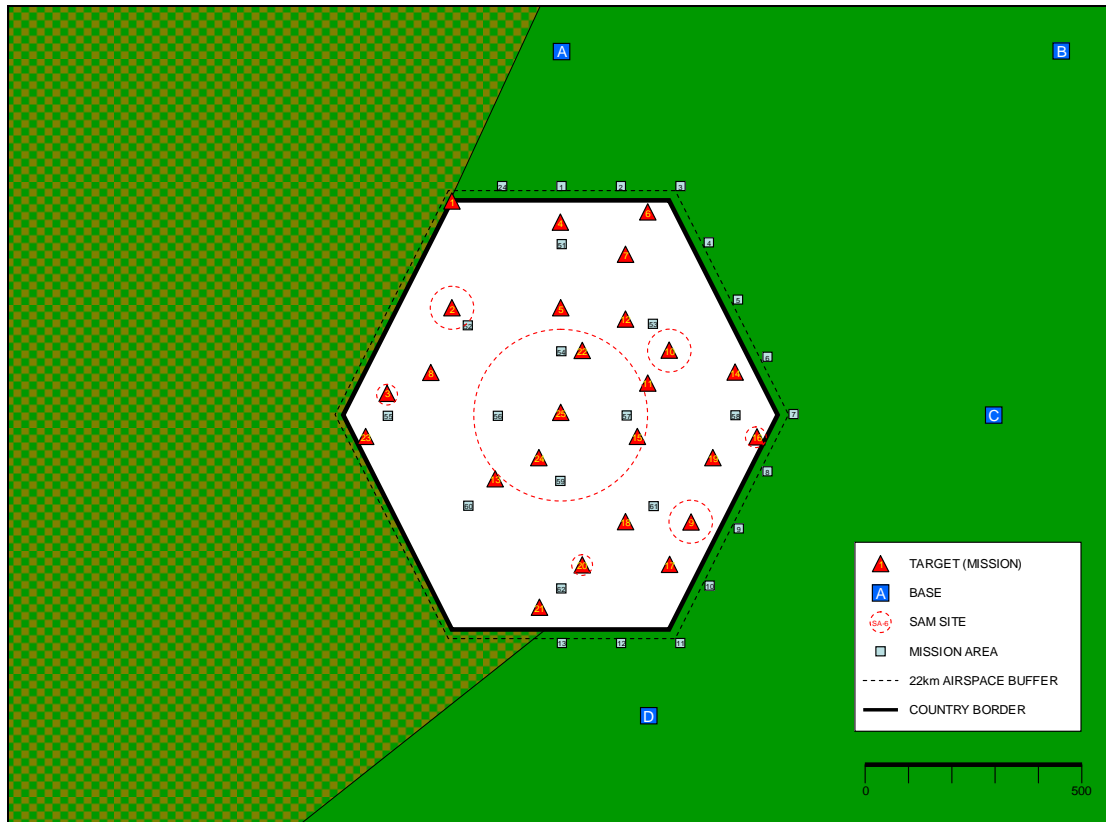


Figure 9. JDAFS Penetrating Scenario as Designed (*Best viewed in color*)

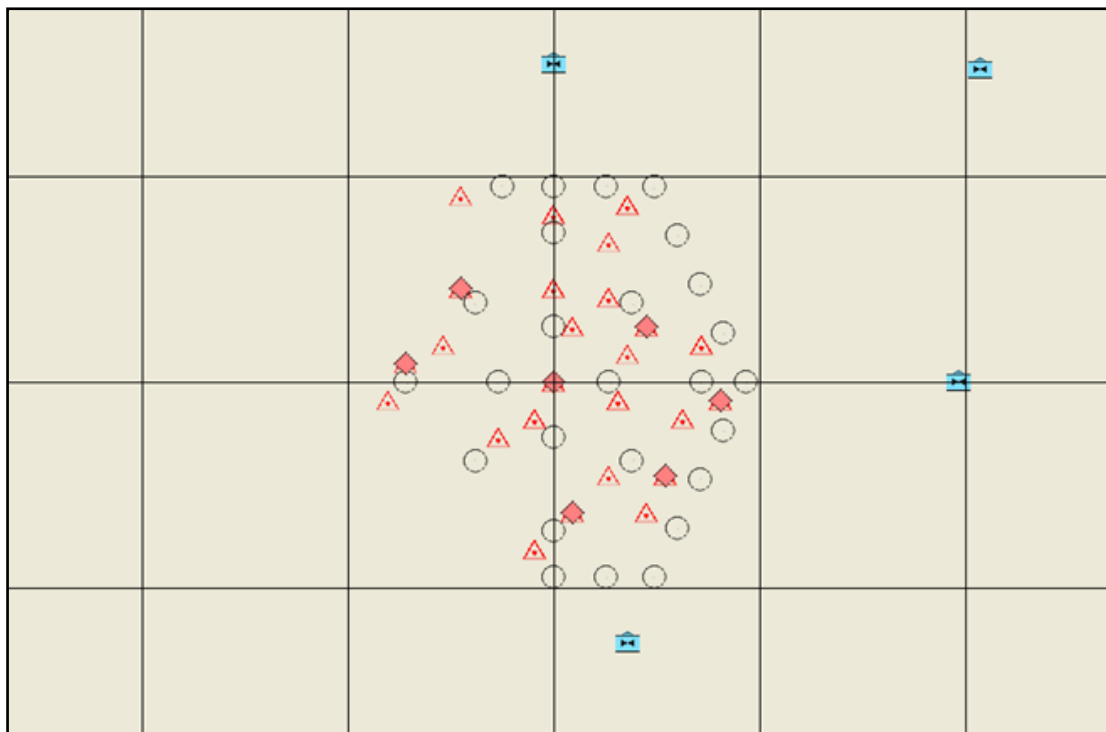


Figure 10. JDAFS Penetrating Scenario in JDAFS GUI (*Best viewed in color*)

## **B. PLATFORMS**

The ISR platforms selected for this study are intended to represent a broad sample of theater and national level capabilities. It is important to note that the airframes used in this simulation are proxies for dissimilar ISR platforms to provide a sense of realism. The platforms are in no way, implicitly or explicitly, intended to reflect real world classified operational capabilities.

### **1. RQ-1 Predator**

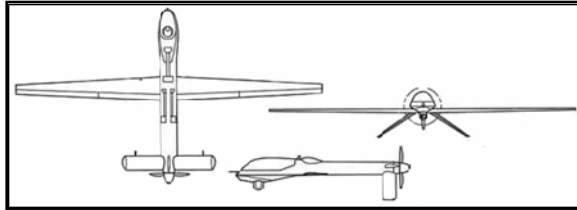


Figure 11. RQ-1 Predator (From Global Aircraft 2007)

The RQ-1 Predator is a medium altitude and endurance unmanned aerial vehicle that carries EO/IR and SAR sensors.

### **2. RQ-4 Global Hawk**

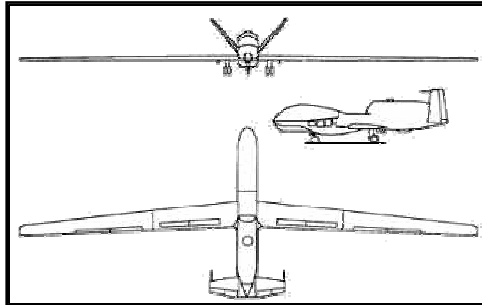


Figure 12. RQ-4 Global Hawk (From Tech-Writer.net 2007, accessed 07 May 2007)

The RQ-4 Global Hawk is a high altitude long endurance unmanned aerial vehicle that carries EO/IR, SAR and ELINT sensor payload packages.



### 3. P-3C Orion

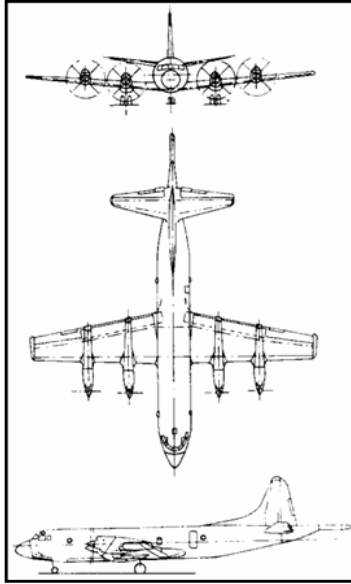


Figure 13. P-3C Orion (From Aerospaceweb.org 2007, accessed 07 May 2007)

The P-3C (AIP) Orion is a manned all-weather day-night long endurance maritime patrol aircraft that carries EO/IR, SAR and ELINT sensor payload packages.

### 4. RC-135 Rivet Joint

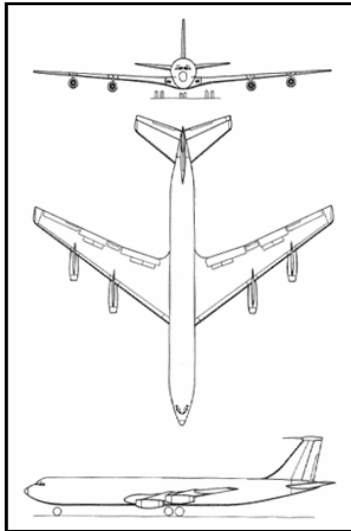


Figure 14. RC-135 Rivet Joint (From Aerospaceweb.org 2007, accessed 07 May 2007)

The RC-135 Rivet Joint is a manned all-weather day-night Signals Intelligence (SIGNINT) collection platform.

## 5. U-2 Dragon Lady

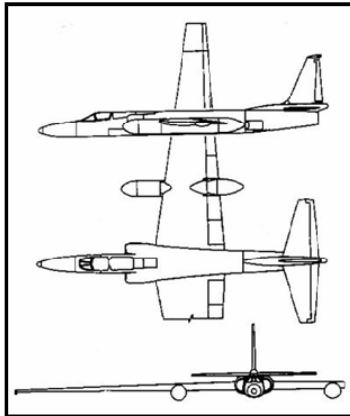


Figure 15. U-2 Dragon Lady (From Aerospaceweb.org 2007, accessed 07 May 2007)

The U-2 is a manned high altitude reconnaissance aircraft with EO/IR, SAR, and ELINT packages.

The operational parameters used in JDAFS for this thesis are listed in Table 3.<sup>9</sup> For real world studies conducted in a classified environment, operational parameters would be provided by the organization sponsoring the research.

PLATFORM	MAX ALTITUDE (meters)	SPEED (meters/hour)	ENDURANCE (hours)	TRANSITION TIME (hours)
RQ-1	8000	148160	24	1.5
RQ-4	18500	629860	36	1.5
P-3	9000	422256	12	1.5
RC-135	10700	805629	11	1.5
U-2	21500	824140	10	1.5

Table 3. ISR Platform Performance Parameters

<sup>9</sup> The operational parameters for the aircraft in this study are approximations based on a variety of open-source references.

## C. SENSORS

The sensors used in this study are implemented as cookie-cutter sensors with a defined footprint and probability of detection of 1.0 (i.e., if a target falls within a sensor's footprint, it will be detected). Other sensor capabilities may be available in future versions of JDAFS.

### 1. Electro-Optical/Infrared (EO/IR)

Electro-optical and infrared sensors are combined for the purposes of this research due to their similarity in detection ranges. EO sensors are day only sensors that produce images based on visible light, similar to standard photographs. IR sensors are day/night sensors that produce images based on thermal differences. IR sensors typically perform better at night when the surrounding environment tends to be cooler than the target of interest.



EO IMAGE



IR IMAGE

Figure 16. EO and IR Images over Bosnia (After Global Defense Review 1997)

### 2. SAR

The Synthetic Aperture Radar (SAR) sensor is an all weather day/night sensor that uses reflected radar energy to create an image of an area or items of interest on the

ground. Due to the characteristics of SAR, this sensor's actual performance is more closely approximated by the cookie-cutter sensor implementation than either the EO/IR or SIGINT sensors.



Figure 17. SAR Image of the Pentagon (After Sandia National Laboratories 2006)

### **3. SIGINT**

Signals Intelligence (SIGINT) sensors monitor the electromagnetic spectrum for signals of interest based on the ISR platform's sensor payload abilities and mission tasking. The SIGINT sensors for this study do not differentiate between communications intelligence (COMINT) and electronic signals intelligence (ELINT) payloads nor whether the target is emitting, only whether the target can be collected against based on the footprint of the cookie-cutter sensor.

### **4. Sensor Ranges**

The sensor ranges used in JDAFS for this thesis are listed in Table 4 and displayed graphically in Figure 18. For real world studies conducted in a classified environment, the sensor ranges and detection parameters would be provided by the organization sponsoring the research.

PLATFORM	SENSOR	RANGE (meters)
P-3	EO/IR	75000
P-3	SAR	200000
RC-135	SIGINT	300000
RQ-1	EO/IR	50000
RQ-1	SAR	200000
RQ-4	EO/IR	75000
RQ-4	SAR	200000
RQ-4	SIGINT	300000
U-2	EO/IR	100000
U-2	SAR	250000
U-2	SIGINT	400000

Table 4. ISR Platform Sensor Ranges

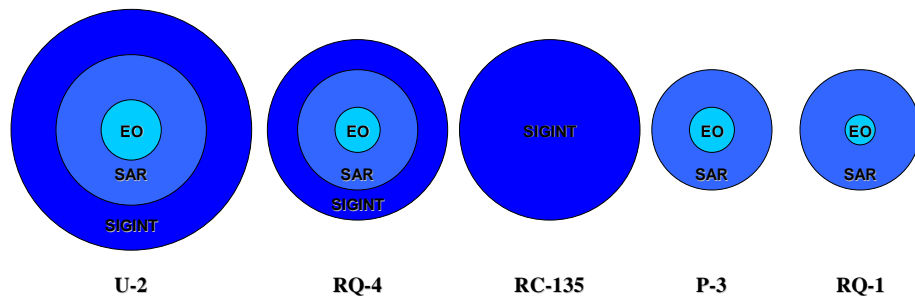


Figure 18. Cookie-Cutter Sensor Footprints

#### D. CONSTRAINTS, LIMITATIONS, AND ASSUMPTIONS

The use of modeling and simulation inherently involves constraints, limitations, and assumptions. As defined in the ASC-U User's Manual, "Constraints are conditions imposed upon the development that are not under the control of the developers. Limitations are self-imposed and are due to choices that the developers of ASC-U made to limit the scope of the problem. Assumptions are those choices made to simplify the problem for ease of solution" (Ahner et al. 2006c, 9).

##### 1. Constraints

- JDAFS improvements are limited to those achievable in a three month development window.
- This study does not consider cueing from other assets that indicate a need for greater fidelity in the resolution on ISR information required.
- No space or ground based assets are included in this study.

## **2. Limitations**

- Performance data is not readily available due to a lack of performance/capability databases and classification of most relevant data beyond the UNCLASSIFIED level.
- No consideration is made of weather or environmental effects on sensor performance.
- LOS is based on visual horizon calculations only, no terrain features are modeled.
- The number and location of targets is fixed.
- Collection platforms operate only at fixed maximum platform altitudes.
- Collection platforms operate at fixed speeds, there is no difference between patrol and ingress/egress speeds.
- The model currently has a limited number of entities that can be included in the simulation without overwhelming the LpSolver routine. The maximum number of entities varies based on the type of scenario and the optimization interval.
- Platforms can not detect targets during ingress or egress.
- Platforms cannot travel from mission area to mission area.

## **3. Assumptions**

- The main factor in determining success of sensors is line-of-sight to target. The effects of weather and environmental factors are neglected. These do not significantly effect SAR sensors, but can significantly impact EO/IR sensors.
- CONOPS of airborne platforms is at maximum altitude perpendicular to mission area location.
- No camouflage, concealment, or deception is employed.
- At least two operating bases will be available.
- Platforms penetrating adversary national air space will be attacked.
- Platforms outside adversary national air space cannot be attacked.
- Platform speeds are constant.
- Cycle time between missions is constant.
- Platforms do not have emergent maintenance problems resulting in lost sorties.
- The number of targets is constant, there are no pop-up targets.

- There are no mobile targets.
- All UAV control and datalink requirements are met.
- Atmospheric conditions do not affect collection, control, or transmission.

## IV. MOE, DOE, AND RUN EXECUTION

### A. MEASURES OF EFFECTIVENESS (MOE)

Three primary MOEs are of interest for analysis in this experiment: Coverage, Coverage by Type, and Attrition. The attrition MOE is only applicable to the penetrating scenario since, by design, the ISR platforms cannot be attacked if they do not violate the COI's airspace. JDAFS records numerous other data elements that could contribute to the analysis of other MOEs, as required.

#### 1. Coverage

Coverage is the amount of time each Mission is covered by an ISR platform. In support of this MOE, JDAFS records the following (See Figure 19):

- **Replication:** Number indicating the simulation run which provided the data.
- **Mission:** The name of the Mission. For this study, the mission name is a numerical code where the number before the decimal represents the mission name (See Table 1) and the number after the decimal identifies the type of sensor required to cover the mission (x.1 = EO/IR, x.2 = SAR, x.3 = SIGINT).
- **Open Time:** The total time, in hours, that the mission was vulnerable to coverage by the required sensor.
- **Covered Time:** The total amount of time, in hours, that the mission was covered by the required sensor.
- **Coverage:** The percentage of time that the missions were covered by at least one sensor during the replication.
- **Value Rate:** The value received per unit time by the covering platform.
- **Total Value:** The total value obtained from this Mission during the scenario.

replication	Mission	openTime	coveredTime	coverage	valueRate	totalValue
1	1.3	240	220.22436	0.917601	1	220.2244
1	2.1	240	67.872923	0.282804	1	67.87292
1	2.2	240	68.5271731	0.28553	1	68.52717
1	2.3	240	227.174711	0.946561	1	227.1747
1	3.1	240	0	0	1	0
1	4.1	240	220.782606	0.919928	1	220.7826

Figure 19. Coverage Data Table Example



## 2. Coverage by Type

Coverage by Type is the amount of time each Mission is cover by each type of ISR platform. In support of this MOE, JDAFS records the following (See Figure 20):

- **Replication:** Number indicating the simulation run which provided the data.
- **Mission:** The name of the Mission. For this study, the mission name is a numerical code where the number before the decimal represents the mission name (See Table 1) and the number after the decimal identifies the type of sensor required to cover the mission (x.1 = EO/IR, x.2 = SAR, x.3 = SIGINT).
- **Mission Platform Type:** The type of platform assigned to the Mission.
- **Open Time:** The total time, in hours, that the mission was vulnerable to coverage by the required sensor.
- **Covered Time:** The total amount of time, in hours that the mission was covered by the required sensor.
- **Coverage:** The percentage of time that the mission was covered by at least one sensor during the replication.
- **Value Rate:** The value received per unit time by the covering platform.
- **Total Value:** The total value obtained from this Mission during the scenario.

replication	Mission	MissionPlatformType	openTime	coveredTime	coverage	valueRate	totalValue
1	1.3	P-3	240	0	0	1	0
1	1.3	RC-135	240	19.21385271	0.08005772	1	19.21385271
1	1.3	RQ-1	240	0	0	1	0
1	1.3	RQ-4	240	213.5448028	0.889770012	1	213.5448028
1	1.3	U-2	240	19.0502298	0.079375957	1	19.0502298
1	2.1	P-3	240	48.82269319	0.203427888	1	48.82269319

Figure 20. Coverage by Type Data Table Example

## 3. Attrition

Attrition represents the number and type of ISR platforms lost. In support of this MOE, JDAFS records the following in the KillerVictimScoreboard table (See Figure 21):

- **Replication:** Number indicating the simulation run that provided the data.
- **Sim Time:** Time in the simulation that the firing event occurred.
- **Firing Platform:** Name of the platform that launched the weapon.
- **Munition:** Type of munition fired by the platform.

- **launch x:** The x coordinate of the firing platform at the time of the firing event.
- **launch y:** The y coordinate of the firing platform at the time of the firing event.
- **weight:** Weight of the munition (not used).
- **Target:** The unique name of the platform targeted.
- **target x:** The x coordinate of the target at the time of the firing event.
- **target y:** The y coordinate of the target at the time of the firing event.
- **type:** Type of platform targeted.
- **target value:** Value of the target (not used).
- **target side:** Affiliation of the target platform.
- **outcome:** Result of the engagement, missed or killed.

Replication	SimTime	Firing_Platform	Munition	launch_x	launch_y	weight	Target	target_x	target_y	type	target_value	target_side	outcome
1	0.826690884	SA-101	SA-10	0	0	1	U-2_1	0	168690.975	U-2	0	Blue	killed
1	2.523543282	SA-6_37	SA-6	50000	-350000	1	RQ-1_13	72226.3106	-348622.3541	RQ-1	0	Blue	killed
1	2.718760643	SA-6_37	SA-6	50000	-350000	1	U-2_9	70792.75866	-344680.0863	U-2	0	Blue	missed
1	2.945224124	SA-101	SA-10	0	0	1	U-2_9	7010.649004	-169279.2848	U-2	0	Blue	killed
1	4.142868882	SA-2_12	SA-2	-250000	250000	1	RQ-1_1	-261357.3946	294615.5364	RQ-1	0	Blue	killed
1	8.206269191	SA-101	SA-10	0	0	1	RQ-1_14	74908.41726	-168360.7734	RQ-1	0	Blue	missed

Figure 21. Killer Victim Scoreboard Example

## B. DESIGN OF EXPERIMENT

A design of experiments is a structured scientific approach to determining how various input parameters, or factors, impact the results of an experiment. In order to fully explore a model's output, a plan must be in place to ensure the collection of data representative of the model's entire response surface. In computer simulation experiments, the understanding of model behavior and response is often best done through the use of data farming.

The concept of data farming originated in 1998 and was further developed by Marine Corps Warfighting Laboratory's Project Albert. Data farming is built on "distributed and high-performance computing; agent-based simulations and rapid model development; knowledge discovery methods; high dimensional data visualization techniques; design-of-experiments methods, human-computer interfaces; team work and

collaborative environments; and heuristic search techniques” (Horne and Meyer 2004, 807-808). This collection of techniques and enabling technologies allows a comprehensive examination of the model.

JDAFS is not currently configured to take full advantage of the data farming concept, but is likely to include future updates to integrate data farming features. For this study, the design of experiments, distributed computing, post-processing of output, and analysis all occur in a piecemeal manner.

## **1. Factors**

Given a database input format and instance (scenario), any possible data element in the database is a potential design factor. Practically speaking, however, for a model such as JDAFS, large groups of data elements together can constitute a single factor. The factors to be varied in this study are the number of each type of aircraft assigned to each base and the optimization interval. Of the 21 total factors, there are 12 integer factors with 4 levels, 8 integer factors with 7 levels, and 1 continuous factor.

### ***a. Assets Assigned to Bases***

The number of each type of aircraft assigned to each base make up the majority of factors for this experiment. There are 4 bases (A, B, C, and D) and 5 types of aircraft (RQ-1, RQ-4, P-3, RC-135, and U-2), for a total of 20 ‘Assets Assigned to Bases’ factors. This factor type is exclusively integer since is not possible to have fractional aircraft. A listing of all of the types of aircraft assigned to each base and the ranges for each factor can be found in Table 5.

<b>FACTOR</b>	<b>MAX</b>	<b>MIN</b>	<b>TYPE</b>
BASE A – RQ-4	3	0	INTEGER
BASE A – RQ-1	6	0	INTEGER
BASE A – P-3	6	0	INTEGER
BASE A – RC-135	3	0	INTEGER
BASE A – U-2	3	0	INTEGER
BASE B – RQ-4	3	0	INTEGER
BASE B – RQ-1	3	0	INTEGER
BASE B – P-3	6	0	INTEGER
BASE B – RC-135	6	0	INTEGER
BASE B – U-2	3	0	INTEGER
BASE C – RQ-4	3	0	INTEGER
BASE C – RQ-1	3	0	INTEGER
BASE C – P-3	6	0	INTEGER
BASE C – RC-135	6	0	INTEGER
BASE C – U-2	3	0	INTEGER
BASE D – RQ-4	3	0	INTEGER
BASE D – RQ-1	3	0	INTEGER
BASE D – P-3	6	0	INTEGER
BASE D – RC-135	6	0	INTEGER
BASE D – U-2	3	0	INTEGER

Table 5. Factors: Assets Assigned to Bases

***b. Optimization Interval***

Optimization interval is the elapsed time in the simulation between optimization events. This factor can take on any continuous value greater than zero. Optimization intervals of greater than 24 hours do not make sense operationally, but there is nothing that prevents an analyst from choosing a longer interval. For optimization intervals that exceed the set scenario length, only an initial optimization would be determined and the simulation would run to completion based on this condition. The range of the optimization interval was limited to between 0.5 and 6 hours for this experiment (See Table 6). Preliminary JDAFS test runs indicate that optimization intervals of less than 0.5 hours result in excessive runtimes.

<b>FACTOR</b>	<b>MAX</b>	<b>MIN</b>	<b>TYPE</b>
OPTIMIZATION INTERVAL	6	0.5	CONTINUOUS

Table 6. Factor: Optimization Interval

## 2. NOLH

Any number of DOE constructs could have been utilized to perform this experiment, such as, sequential bifurcation, folded sequential bifurcation,  $2^{k-p}$  fractional factorial, combined designs, or Nearly Orthogonal Latin Hypercube (NOLH) designs, among others (Sanchez 2006; Kleijnen et al. 2005). However, given the number of factors in this study, not all of the DOE applications would have been tractable. For example, a full factorial design with only 3 levels for each factor would result in  $3^{21}$  or 10,460,353,202 design points. Assuming, only the deterministic non-penetrating scenario was to be executed and each run took a nominal 5 minutes to complete, the total processing time required would be nearly 1,000 years. Fortunately, alternatives exist that keep the run time at a practical level while ensuring a meaningful exploration of the response surface.

The Nearly Orthogonal Latin Hypercube is such a design. The NOLH design provides a number of highly desirable DOE qualities including: orthogonality, space filling and bias protection, efficiency, and flexibility.

- Orthogonality<sup>10</sup>, or near orthogonality, is important to ensure independence of the regressors, or coefficient estimates in regression models. This property significantly enhances the ability to evaluate the suitability of factors for inclusion in the resultant metamodel and determine the overall contribution to metamodel fit (Kleijnen et al. 2005).
- Space-filling designs enable the exploration of all regions of the response surface, not just the edges. By distributing the design points throughout the experimental region, analysts can minimize the number of assumptions made about the response surface. Additionally, “Space-filling designs also provide flexibility when estimating a large number of linear and nonlinear effects, as well as interaction, and so provide general bias protection when fitting metamodels of specific forms” (Kleijnen et al. 2005, 274).
- The NOLH design provides efficiency in allowing the rapid determination of the correct minimum number of design points necessary for an experiment. Additionally, with the use of a NOLH design template, an experimenter can quickly produce a design containing numerous factors with multiple or continuous levels.

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<sup>10</sup> Orthogonality exists when the inner product of any two columns of a matrix is equal to zero.

- The NOLH design is extremely flexible. Factors of interest can rapidly be added or levels can be changed to provide more insight into a model or to create entirely new designs. NOLH designs can also be stacked to achieve more desirable pairwise correlation or specific design points of interest can be appended to any existing design.

For this study, a NOLH DOE was constructed using the NOLHDesigns\_v4.xls worksheet (See Figure 22) created by Dr. Susan Sanchez (2005) based on algorithms developed by Cioppa (2002). The worksheets have been crafted specifically to avoid the problems associated with multicollinearity and ensure a robust space-filling design. This worksheet, capable of handling up to 29 factors, is available at < <http://harvest.nps.edu/>>. Five templates are included in the workbook to facilitate designs with various numbers of factors; 8-11, 12-16, 17-22, and 23-29. Each template can be used for any number of factors up to the maximum allowed in the template. This allows smaller experiments to be created with more than the minimum number of design points, improving upon the space-filling properties of the design and increasing the number of degrees of freedom for the output data. In this case, the 23-29 factor worksheet was used to create 257 design points<sup>11</sup> based on the 21 factors in the experiment.

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<sup>11</sup> The maximum number of factors in a Latin Hypercube is determined by  $m + combination(m-1, 2)$  where  $m$  is an integer greater than 1. Since the maximum number of factors for the chosen design template is 29, solving the previous equation for  $m$ , yields  $m = 8$ . The number of design points,  $n$ , can be found by  $n = 2^m + 1$ . Therefore, a design that includes 29 factors requires 257 design points.

Microsoft Excel - DOE WORKSHEET

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Security...

Arial 10 B I U

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
2	low level	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5
3	high level	3	6	6	3	3	3	6	6	3	3	3	6	6	3	3	3	6	6	3	3	6
4	decimals	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
5	factor name	AR0-4	AR0-1	AP-3	ARC-135	AU-2	BR0-4	BR0-1	BP-3	BRC-135	BU-2	CR0-4	CR0-1	CP-3	CRC-135	CU-2	DR0-4	DR0-1	DP-3	DRC-135	DU-2	OPT INT
6		1	5	4	2	2	3	6	5	1	0	1	2	0	1	1	1	3	0	0	1	2
7		0	2	5	3	2	2	6	5	2	2	2	4	6	3	2	0	0	1	0	1	3.7
8		0	4	1	2	3	2	6	5	2	1	1	1	1	0	3	2	3	6	3	1	1
9		1	1	2	2	2	2	5	6	0	2	3	5	6	3	2	2	5	6	2	0	1.3
10		1	3	4	1	3	2	5	4	0	2	0	0	2	0	2	0	1	1	1	3	4.1
11		1	2	6	0	3	3	4	6	2	1	3	5	5	2	3	1	2	3	1	3	5.3
12		0	4	3	0	2	2	5	4	2	2	0	2	2	1	0	3	5	4	3	2	3.2
13		1	0	2	1	3	2	4	4	1	0	1	3	5	2	1	3	4	5	2	2	5.2
14		0	3	6	2	1	2	4	6	1	1	3	1	3	1	1	2	2	2	1	2	1.5
15		1	0	5	2	0	2	3	3	3	2	1	4	5	3	0	2	3	1	1	2	3.2
16		0	6	3	3	1	2	6	4	3	1	2	1	1	1	2	0	5	3	2	3	2.9
17		0	1	0	2	1	2	5	4	1	3	1	3	6	2	2	1	4	5	3	2	1.9
18		1	6	4	0	1	2	4	4	1	3	2	1	0	1	2	2	2	0	1	1	4.4
19		0	2	4	0	0	2	6	3	2	1	1	5	4	2	2	3	3	2	1	1	3.3
20		1	4	0	1	0	2	5	3	2	3	2	2	2	0	0	1	5	6	2	0	5.1
21		1	2	2	0	1	2	6	5	0	2	0	3	5	2	1	1	4	4	2	1	4.8
22		1	3	5	2	3	1	4	4	0	1	2	4	1	1	1	1	5	1	0	1	5.2
23		1	2	5	2	2	1	5	4	2	2	3	1	4	2	1	1	5	1	0	1	3.8
24		1	5	3	2	2	0	5	5	2	1	1	4	1	0	2	2	2	5	2	0	5.7
25		1	1	2	2	2	1	5	6	1	1	2	0	5	2	2	3	2	4	2	1	5.8
26		1	3	5	1	2	0	6	6	1	2	0	5	1	1	3	1	6	1	1	2	1.3
27		1	2	4	1	3	0	5	5	2	0	2	0	6	3	1	1	3	1	1	2	0.9
28		1	5	3	1	2	1	5	4	2	2	1	5	1	1	1	3	1	5	3	1	2
29		1	2	2	1	2	0	5	4	1	1	1	3	4	2	1	2	0	6	3	2	2.4
30		1	3	5	3	1	1	3	6	0	1	2	5	2	0	1	2	5	2	1	2	3.3
31		1	2	5	2	1	0	4	5	2	3	1	2	3	3	1	2	3	2	0	1	5.3
32		0	5	3	2	1	1	4	5	2	1	2	3	2	1	2	1	1	5	3	2	5.7
33		1	1	2	2	1	1	4	3	1	2	2	3	3	2	3	1	2	3	3	2	3.7
34		1	5	5	1	1	1	5	5	1	3	2	5	1	1	3	2	3	3	0	1	2.9
35		1	2	3	0	1	0	5	3	3	1	0	3	5	2	2	1	5	2	0	1	3.4
36		1	5	1	1	1	0	4	5	2	2	2	4	2	0	0	1	1	5	2	1	1.7
37		0	3	2	1	1	1	3	6	1	1	1	1	4	3	1	0	3	5	2	0	2.7
38		1	4	5	2	2	3	1	4	1	1	0	0	3	1	0	1	1	4	0	0	1.7
39		1	3	5	2	3	3	3	3	3	2	2	6	1	2	1	1	0	6	1	0	1.8
40		1	5	2	2	3	3	1	3	2	1	1	1	5	0	2	3	6	2	2	1	2
41		0	2	3	2	2	3	2	6	1	2	3	6	1	2	2	2	6	2	2	0	0.9
42		1	4	3	0	3	2	1	5	1	2	0	2	6	1	1	0	1	4	1	2	5.4
43		1	2	4	1	3	2	1	3	2	1	3	5	1	3	2	0	1	4	1	2	5.5
44		1	3	2	1	2	2	3	4	2	2	0	2	5	1	1	3	4	0	2	3	5.9

readme / gpl / OHL for 2-7 factors / NOHL for 8-11 factors / NOHL for 12-16 factors / NOHL for 17-22 factors / NOHL for 23-29 factors

Draw AutoShapes

Ready NUM

Figure 22. Nearly Orthogonal Latin Hypercube Worksheet.

The design created consists of a 257 x 21 matrix with a maximum pairwise correlation of 0.0942.<sup>12,13</sup> Figure 23 provides a scatterplot of the design factors demonstrating the space-filling properties of the NOLH design. The uniform appearance of the points in the scatterplot is due to the integer structure of the 20 Assets Assigned to

<sup>12</sup> Ideally, the maximum pairwise correlation should be less than 0.03 to classify a matrix as nearly orthogonal. The 0.0942 achieved in the design for this study is low enough given the resolution of the model. Creating a design with a maximum pairwise correlation with the factors used in this study would have required more than doubling the number of design points. The runtime for this new design would have been impractical. (Cioppa 2002).

<sup>13</sup> Lower correlation numbers can be achieved, if required, by creating a stacked NOLH design. This is done by pasting the values from the NOLH worksheet into a new worksheet. Then, randomly permuting the column headings in the original NOLH worksheet and pasting those values into the new worksheet containing the values from the original worksheet, ensuring that the values in the columns are matched to the correct column headings. This results in a design with the same number of columns, but twice as many rows as the original design.

Bases factors. The space-filling patterns would be dramatically different if the factors were continuous in nature. An additional 17 special case design points were added, resulting in a 274 x 21 final design matrix.

The special case design points are added to explore the response at specific combinations of factor settings that were not captured by the NOLH design. The first 15 design points represent all possible combinations of 1, 2, 3, and 4 base configurations with maximum aircraft availability, 21 aircraft at each open base, and a midpoint setting of the optimization interval, 3.25 hours. The 2 remaining design points are for 4 base configurations with maximum aircraft availability and optimization intervals set at the minimum and maximum, 0.5 and 6 hours, respectively.



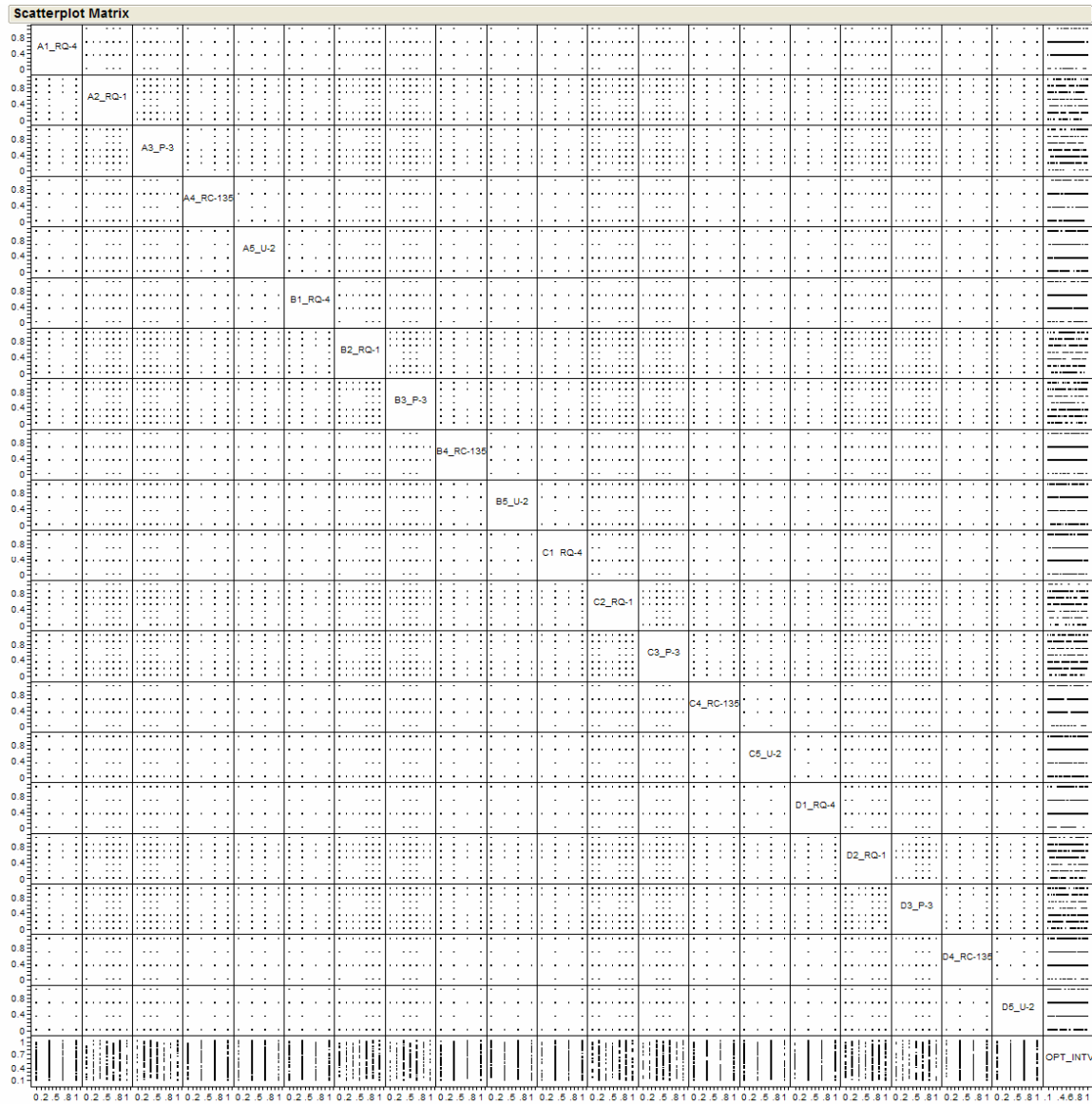


Figure 23. Scatterplot Matrix for Design Factors

Additional information on NOLH can be found in Cioppa's (2002) Efficient Nearly Orthogonal and Space-Filling Experimental Design for High-Dimensional Complex Models doctoral dissertation.

## C. EXECUTION OF SCENARIOS

### 1. Implementing DOE

In executing an experiment, the DOE determines the number of design points, but the number of replications must be decided upon by the analyst. A deterministic model needs only a single run of each design point. No matter how many times the experiment is run, a deterministic model always returns the same result. Selecting the number of replications necessary for a stochastic model is more challenging. Unfortunately, no clear rules exist that allow a determination of the “right” number of replications *a priori*. The number of replications must “gain enough data to achieve narrow confidence intervals and powerful hypothesis tests” (Sanchez 2006, 69). Conduct too few replications and the experiment may have to be rerun to get more data, too many replications and valuable resources may have been wasted (Chung 2004).

For the purposes of this study, the non-penetrating scenario is purely deterministic and requires only one replication of each design point. The penetrating scenario, however, has the stochastic element of probability of kill ( $P_k$ ) for the SAMs. The use of 10 replications of each design point for the penetrating scenario was all that was feasible given the scope of this research, processing constraints, and time limitations.

A method was developed for JDAFS so that the analyst can specify which input factors are to be varied, match those factors with a design, and generate the corresponding input database. This was done so that there was no impact whatsoever on the basic input database design, and so that the specific experimental design used was completely interchangeable. That is, the analyst could keep the same basic input scenario and same set of factors, but swap in any experimental design scheme that was desired with only a minimal amount of changes. For each design point, the DesignGenerator (See Figure 24) program uses SQL statements to create a corresponding input file. JDAFS writes its output reports to the same database that was used for input, so there is always a direct association between input and output values.

Execution of JDAFS is oriented towards a single run with a single input file; there is no built-in capability in JDAFS itself to run experimental designs. Yet executing JDAFS with various input factors set based on efficient designs is essential to its effective use. The normal input to a JDAFS scenario is currently via an Access database; support for other databases such as MySQL, Oracle, and Derby will be added to future versions of the program.

Setting a factor requires more than changing a single value; all data elements in columns corresponding to that factor must be changed to correctly set the factor to its appropriate level. In order to use the DesignGenerator, the values in the NOLH worksheet must be normalized to a range of [0, 1] and saved in plain-text comma-separated (csv) files. Conceptually, these files constitute tables in a virtual database (and future versions will be implemented as such); therefore, these tables of values are represented as a database called “Designs.” Different schemes can be used to generate these tables of values without modifying any other part of the input or the code.

The Factors database consists of two tables: one to identify factors in the template database by table and column, together with a user-specified minimum and maximum value; and a second table that maps the number of factors (determined by the number of rows in the first table) to one of the design point files. That table is then read, and the corresponding values applied to the minimum and maximum values to produce an input value. The “DesignGenerator” program that does this is written in Java and uses Java Database Connectivity (JDBC) to access the databases. Hence, using different databases only requires that a different JDBC driver be installed.

For each design point, the DesignGenerator program uses SQL statements to create a corresponding input file, which is numbered <name>xxxx.mdb, where “xxxx” is an index corresponding to the particular design point index. All the input from the template database is copied, and those entries that are factors are modified using the SQL UPDATE query to be set to the design point values. An additional table is written that identifies the particular names and values of the input factors. This information is used after JDAFS is executed to extract the independent and dependent variables for statistical analysis.

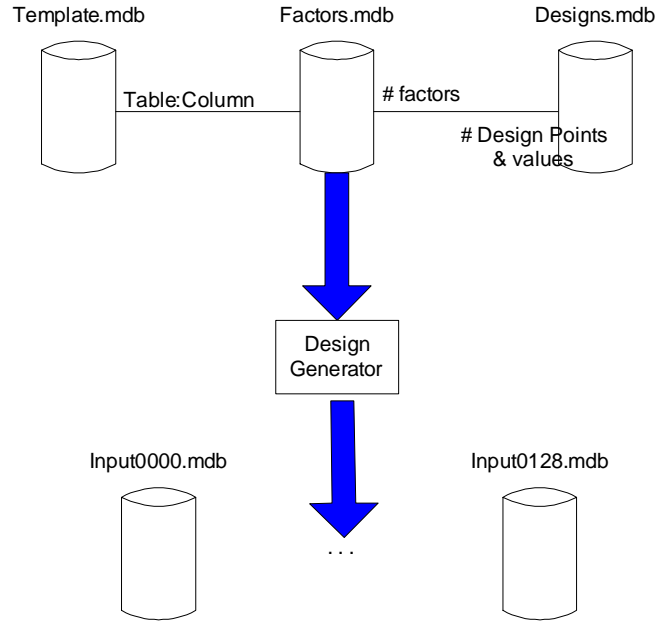


Figure 24. Design Generator for Producing Input Files

## 2. Computing Resources

While JDAFS is capable of running on standalone laptop or desktop computers, it is impractical to run simulation experiments requiring hundreds or possibly millions of runs, each potentially requiring several hours of runtime, on anything but a computing cluster. For this particular experiment, the non-penetrating scenario required 274 runs and the penetrating scenario required 2740 runs (274 x 10). These production runs were executed by Dr. Paul Sanchez, Senior Lecturer in the Operations Research Department at the Naval Postgraduate School, on the Simulation Experiments & Efficient Designs (SEED) Center Microsoft Windows computing cluster located at TRAC-Monterey on the NPS campus in Monterey, CA. The SEED Center computing cluster is composed of 12 dual processor Dell desktops with 2G of RAM, running Windows XP. The machines are using Condor cluster software, which is open source software available from the University of Wisconsin <<http://www.cs.wisc.edu/condor/>>. The individual computers have Cygwin software <<http://www.cygwin.com/>> installed to enable improved command line tools, remote access via Secure Shell, and sophisticated scripting. The non-penetrating scenario runs were completed in approximately 4 hours and the penetrating scenario runs in approximately 60 hours.

### 3. Post-processing of JDAFS Output

Upon completion of the JDAFS model runs on the SEED Center computing cluster, the output data is written to tables in the input database. Therefore, 274 separate output databases are created, one for each design point in the scenario. By writing the output reports to the same database that was used for input, there is always a direct association between input and output values. The independent input/output databases must be combined into a consolidated database prior to performing any further analysis.

The process for combining the independent output databases into a single common output database is essentially the reverse of creating the design databases. An OutputGenerator (See Figure 25) was created in JAVA using SQL statements to create a single output database. Like the DesignGenerator, JDBC is used to access the databases in the OutputGenerator. The OutputGenerator appends the information in the individual output database tables to like tables in the common output database. Since the JDAFS output data is written in string format, individual columns of data that should be numeric must be converted to the proper format prior to any data analysis.

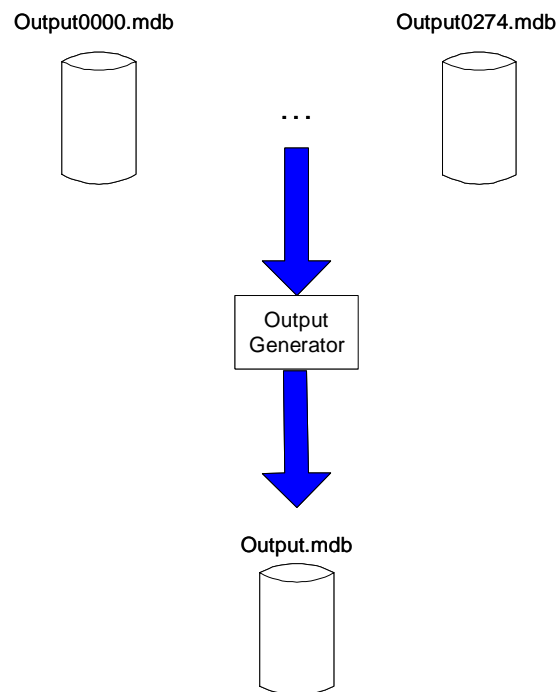


Figure 25. Output Generator for Producing Output Files

The cumulative size of the output databases at the completion of the simulation runs was over 7.5 gigabytes. The process of combining the output databases into a single database for each scenario reduced the overall file size to approximately 470 megabytes. This was further reduced to just over 300 megabytes by converting the output database tables into tables in JMP.

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## **V. ANALYSIS**

A detailed pre-simulation analysis of the scenarios and a post-simulation analysis of the output data collected from the execution of this study's penetrating and non-penetrating scenarios were conducted. The following chapter describes the analysis process and relevant discoveries and points of interest from this research.

### **A. ANALYSIS METHODOLOGY, TECHNIQUES, AND TOOLS**

#### **1. Methodology**

The same analysis methodology is applied to both scenarios, non-penetrating and penetrating, in this experiment. Pre-simulation spreadsheet analysis was conducted to gain an understanding of how the scenario design would impact the JDAFS simulation results and to provide the capability to ensure reasonableness of JDAFS output. Upon completion of the simulations, the data from each scenario was used to generate summary statistics to verify the validity of the output and identify outlying data points. The outliers were examined to determine their cause and potential impact on subsequent analysis. Multiple regression analysis was performed to allow the construction of metamodels for each scenario. The validity of these metamodels was confirmed through the use of regression and classification trees. Additional graphical analysis techniques were performed to gain insights and understanding into the behavior and influence of specific factors.

#### **2. Analytical Techniques**

A variety of analytical techniques were applied to fully examine and understand the scenarios and output from this study. The various techniques are complementary to one another and serve to validate the results of the methodology. The techniques applied in this study were spreadsheet, graphical, multiple regression, and classification and regression tree (CART) analysis.



**a. Spreadsheet Analysis**

Spreadsheet analysis enables the rapid examination, manipulation, and display of large amounts of data in a flexible environment. The use of this tool facilitated the construction and evaluation of a variety of easily reconfigurable scenarios that were compatible with the JDAFS input databases and more sophisticated analysis tools. While not suitable for complex post-simulation data analysis, the use of spreadsheets enables a means to examine design scenarios prior to conducting simulation runs.

**b. Multiple Regression**

Regression is a technique that constructs a probabilistic model to examine the relationship between a dependent (response) variable and an independent variable (predictor) (Montgomery et al. 2004). Multiple regression involves more than one regressor or predictor and may contain interaction and quadratic terms. Models with first order predictors, interaction, and quadratic terms are referred to as full quadratic models. The response variable is represented as  $Y$  and the predictor variables as  $x_1, x_2, \dots, x_k$ , where  $k$  indicates the number of regressors. The  $\beta$  parameters,  $\beta_1, \beta_2, \dots, \beta_k$ , are regression coefficients that determine the mean amount of change in  $Y$  for every one unit change in the associated predictor variable while all other predictors are held constant. The  $\beta_0$  parameter is a constant term that indicates the point at which the regression line intersects the y-axis. The error term,  $\varepsilon$ , is a “random variable that accounts for the failure of the model to fit the data exactly” (Montgomery et al. 2004, 1). Also known as the residual,  $\varepsilon_i$  is assumed to be normally distributed with a mean of 0 and a variance of  $\sigma^2$  or  $N(0, \sigma^2)$ . Devore (2004, 588) illustrates four common forms for multiple regression models containing two independent variables,  $x_1$  and  $x_2$ .

1. First order model:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon$$

2. Second order no-interaction model:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \varepsilon$$

3. Model with first order predictors and interaction:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \varepsilon$$

4. Full quadratic model:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 + \varepsilon$$

Regression models must conform to several assumptions in order to be considered valid (Montgomery et al. 2004, 131):

1. The relationship between the response  $y$  and the regressors is linear, at least approximately.
2. The error term  $\varepsilon$  has a zero mean.
3. The error term  $\varepsilon$  has a constant variance  $\sigma^2$ .
4. The errors are uncorrelated.
5. The errors are normally distributed.

These assumptions are summarized as follows:

$$\varepsilon_i \stackrel{iid}{\sim} N(0, \sigma^2), \forall i.$$

Conformity to these assumptions is demonstrated for each of the regression models constructed in this study. The linearity assumption between the response variable  $y$  and the regressors is checked by plotting the regression line against a scatter plot of the data, an actual by predicted plot. The assumptions of a zero mean, constant variance of  $\sigma^2$ , and uncorrelated errors are confirmed through a residual by predicted plot. This is indicated by a mean of zero and a cloud of apparently random data points. Finally, the normality assumption is demonstrated by histogram plot of the residuals overlaid with a normal curve.

For the purposes of this research, up to full quadratic models are constructed by stepwise regression. The wide variety of distances in mission to mission area pairings along with the differences in aircraft and sensor operational parameters result in inherent nonlinearities. These complexities must be accounted for through the use of full quadratic models.

*c. Classification and Regression Trees (CART)*

Classification and regression trees provide a method for recursively partitioning data sets in accordance with the relationship between the response variable and the predictors. Each split creates two branches in an inverted tree structure by considering all possible cuts or groupings and selecting the partition with the largest likelihood-ratio chi-square statistic (JMP Statistical Discovery Software 2006). This method generates a chart that is straightforward to interpret and clearly shows the most significant factors.

*d. Graphical Analysis*

Graphical analysis provides a visual representation of data allowing for rapid interpretation and enhanced understanding. Overlays, bar charts, scatter plots, line graphs, and contour plots were all use in the exploration of the pre- and post-simulation data. Additionally, the graphical representation of relevant findings is of benefit in conveying complex information to individuals or groups not intimately familiar with this topic or the research methods applied.

**3. Analysis Tools**

*a. Microsoft Excel*

Microsoft Excel was used to perform pre-simulation spreadsheet analysis of the scenarios developed for this experiment in order to understand the type of output that might be generated by the actual JDAFS production runs. Additionally, Excel was utilized, where appropriate, for the production of explanatory tables and graphs in the analysis of the simulation output.

***b. JMP Statistical Discovery Software***

The JMP (pronounce ‘jump’) Statistical Discovery Software from SAS is the tool chosen for analysis of the resultant data from the JDAFS model runs. This powerful analysis tool is intuitive to use and does not require additional programming or script writing to obtain results. JMP allows the analyst to interactively investigate data in a dynamically linked spreadsheet and graphical environment. Additionally, JMP provides a journaling function for saving and revisiting graphics or data tables of interest. More information on JMP Statistical Discovery Software can be found on the company’s web site: <<http://www.jmp.com>>.

**B. PRE-SIMULATION ANALYSIS**

**1. Non-Penetrating Scenario**

The non-penetrating scenario limits the collection ability of the ISR platforms to standoff mission areas. This restriction causes the implementation of waypoint routing to prevent COI overflight, thereby requiring additional flight time between bases and mission areas.

***a. Scenario Geometry***

As shown in Chapter III, Table 1, there are 25 targets, each with up to 3 sensor requirements. These 25 targets are broken down into 20 EO/IR, 18 SAR, and 17 SIGINT requirements, for a total of 55 missions. These 55 missions or sensor requirements can be serviced from any of the 14 mission areas in the non-penetrating scenario. (*Satisfaction of sensor requirements depends upon the availability an ISR platform with the correct sensor package, sufficient sensor range and the platform’s ability to meet the minimum altitude to achieve line-of-sight.*) By matching the 14 mission areas with the 55 missions, 770 possible mission area-to-mission pairings are possible; 280 EO/IR, 252 SAR, and 238 SIGINT. See Figure 26 for an example of mission area-to-mission matching. Each of these pairings is taken into account by JDAFS in determining the optimum allocation of ISR platforms.

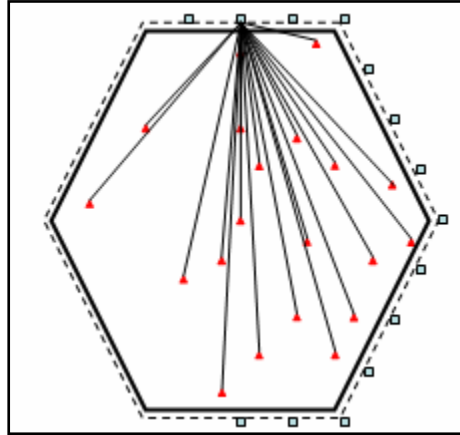


Figure 26. Example of Mission Area-to-Mission Pairings for a Single Mission Area to all EO/IR Missions

It is expected that the lowest absolute distance and the lowest mean and median distance from a base to its associated mission areas will play a significant role in determining the overall coverage achieved by the various ISR platforms. An examination of the basing configuration as shown in Figure 27 and Table 7 reveals the following:

- Base D is closest to its nearest mission area, then A, C, and B, respectively.
- Base C has the lowest maximum distance to its farthest mission area, then D, A, and B, respectively.
- Base D has the lowest mean and median travel distance to its mission areas, then C, A, and B, respectively.

Note that waypoint routing affects the mean and median travel distance in the non-penetrating scenario since the COI airspace cannot be violated.

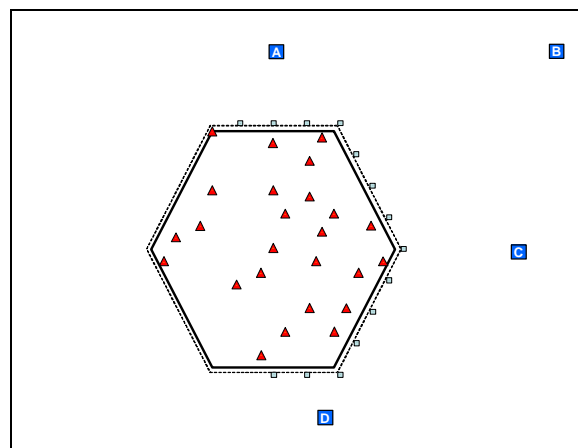


Figure 27. Basing Configuration

SUMMARY OF BASE TO MISSION AREA DISTANCE STATISTICS				
	A	B	C	D
MIN	328000	936862	578000	187840
MAX	1854124	1899964	1390502	1760154
MEAN	974987	1271025	938075	875094
MEDIAN	932023	1197693	920821	842965
All distances are in meters				

Table 7. Non-Penetrating Scenario Summary of Base to Mission Area Distance Statistics (The additional transit required due to waypoint routing to prevent COI overflight is included in the distance calculations for this table).

***b. Sensor Coverage***

Each of the ISR platforms has a differing ability meet the various sensors demands. The requirement to collect from standoff mission areas in the non-penetrating scenario limits the amount of coverage each aircraft can provide. The following figures depict the potential coverage by each type of platform and sensor<sup>14</sup>.

Figure 28 illustrates the potential coverage by the RQ-1 EO/IR and SAR sensors. There are no EO/IR targets and ten SAR targets that can be ranged by the RQ-1.

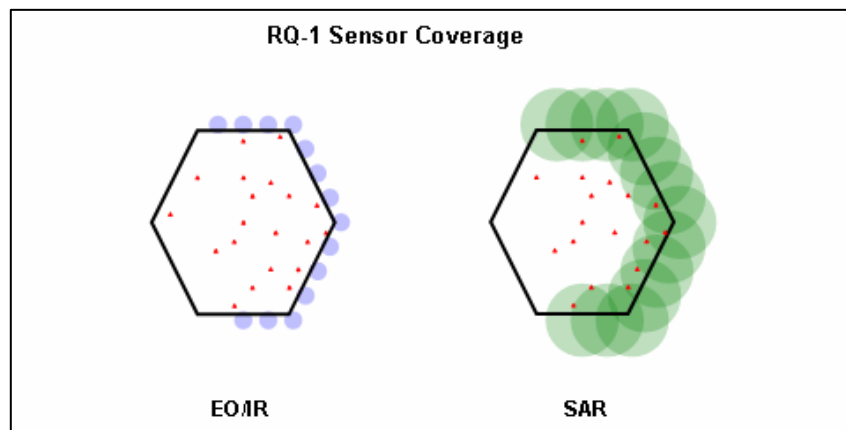


Figure 28. RQ-1 Sensor Coverage for the Non-Penetrating Scenario

<sup>14</sup> Note that the amount of coverage depicted in the illustrations may differ slightly from the amount of coverage that has been calculated due to the imprecise nature of the graphics. In all cases, the text refers to the calculated coverage.

Figure 29 demonstrates the ability of the RQ-4 to cover EO/IR, SAR and SIGINT sensor requirements. The RQ-4 can satisfy 2 EO/IR, 10 SAR, and 13 SIGINT requirements.

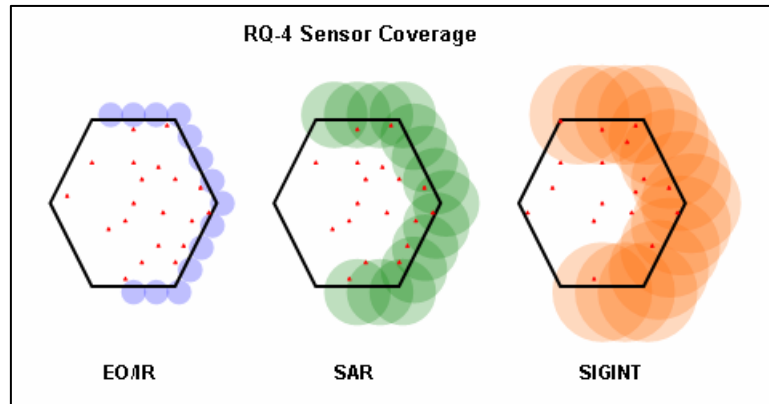


Figure 29. RQ-4 Sensor Coverage for the Non-Penetrating Scenario

The ability of the P-3 to provide EO/IR and SAR coverage is illustrated in Figure 30. The P-3 can range 2 EO/IR missions and 10 SAR missions.

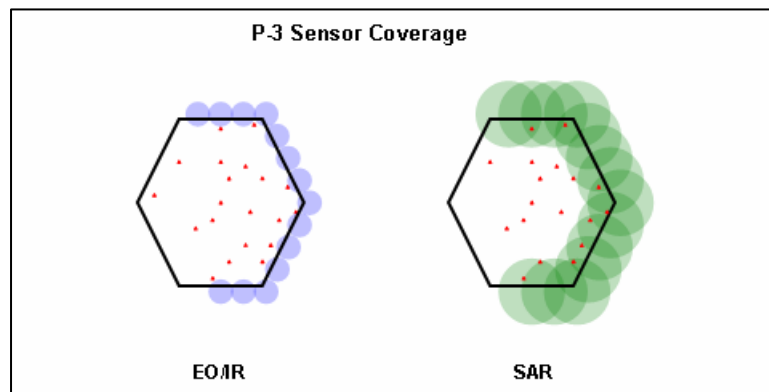


Figure 30. P-3 Sensor Coverage for the Non-Penetrating Scenario

Figure 31 depicts the coverage of the RC-135. The RC-135 has the ability to cover 13 SIGINT sensor requirements.

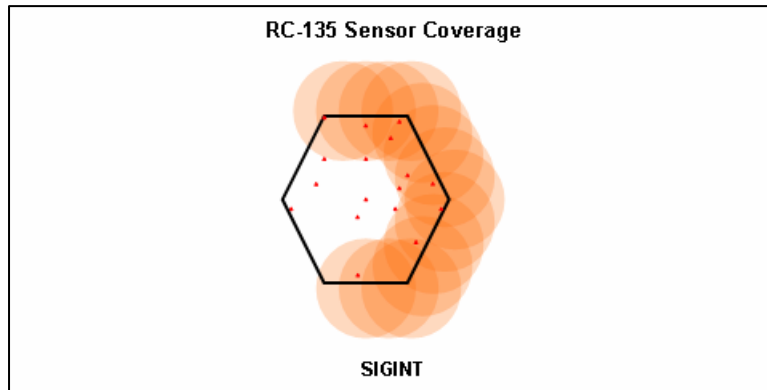


Figure 31. RC-135 Sensor Coverage for the Non-Penetrating Scenario

The U-2's sensor capabilities are shown in Figure 32. The U-2 can satisfy 7 EO/IR, 11 SAR, and 13 SIGINT missions, making it, sensor wise, the most capable platform in the scenario.

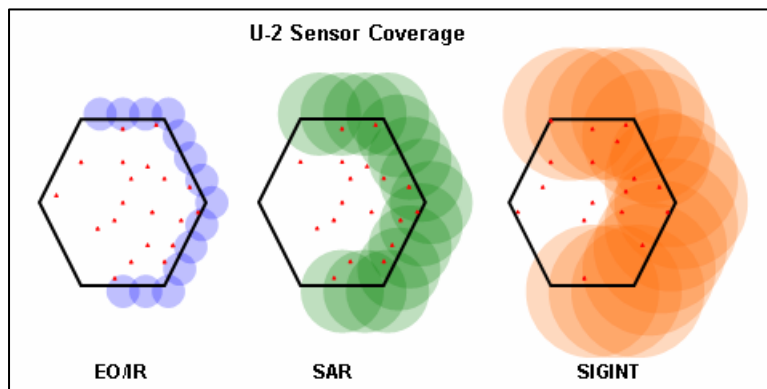


Figure 32. U-2 Sensor Coverage for the Non-Penetrating Scenario

Table 8 provides a summary of the number of missions that can be covered by each ISR platform from each mission area. Ranked by ability to provide coverage of the most targets per mission area, the most capable aircraft is the U-2, followed by the RQ-4, the RC-135, the P-3, and finally the RQ-1. This further demonstrates the U-2's superior ability to provide coverage. Note that the capability of the RQ-1 and the P-3 is very similar, with the P-3 marginally exceeding the RQ-1.



MISSION AREA	RQ-4				RQ-1			P-3			RC-135	U-2			
	EO/IR	SAR	SIGINT	TOTAL	EO/IR	SAR	TOTAL	EO/IR	SAR	TOTAL	SIGINT/TOTAL	EO/IR	SAR	SIGINT	TOTAL
1	1	1	5	7	0	1	1	1	1	2	5	1	2	6	9
2	0	2	3	5	0	2	2	0	2	2	3	1	2	6	9
3	0	1	3	4	0	1	1	0	1	1	3	1	1	5	7
4	0	1	4	5	0	1	1	0	1	1	4	0	2	7	9
5	0	2	5	7	0	2	2	0	2	2	5	0	3	8	11
6	1	2	4	7	0	2	2	1	2	3	4	1	3	6	10
7	0	3	2	5	0	3	3	0	3	3	2	1	3	6	10
8	0	3	4	7	0	3	3	0	3	3	4	1	4	6	11
9	0	3	2	5	0	3	3	0	3	3	2	1	4	5	10
10	0	2	1	3	0	2	2	0	2	2	1	1	2	4	7
11	0	1	1	2	0	1	1	0	1	1	1	0	1	2	3
12	0	1	1	2	0	1	1	0	1	1	1	0	3	2	5
13	0	2	1	3	0	2	2	0	2	2	1	1	2	1	4
24	0	1	3	4	0	1	1	0	1	1	3	0	1	6	7
TOTAL	2	25	39	66	0	25	25	2	25	27	39	9	33	70	112
MIN	0	1	1	2	0	1	1	0	1	1	1	0	1	1	3
MAX	1	3	5	7	0	3	3	1	3	3	5	1	4	8	11
MEAN	0.1	1.8	2.8	4.7	0.0	1.8	1.8	0.1	1.8	1.9	2.8	0.6	2.4	5.0	8.0
MEDIAN	0	2	3	5	0	2	2	0	2	2	3	1	2	6	9

Table 8. Non-Penetrating Scenario: Number of Missions Potentially Satisfied from Each Mission Area by Platform and Sensor Type

Figure 33 compares the ability of the various ISR platforms to provide coverage. Note that the U-2 is superior to all other aircraft in every category. This difference is due to the U-2's advantage in sensor range for all types of sensors.

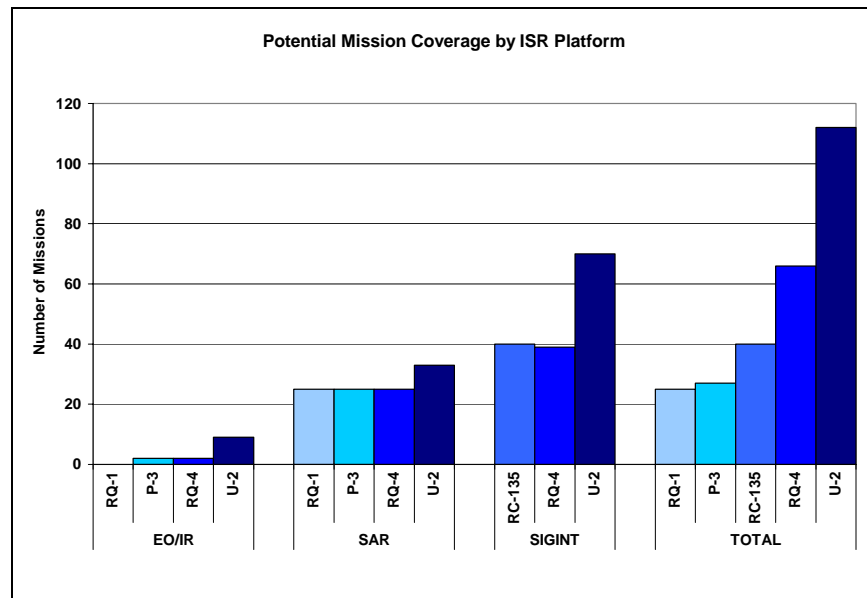


Figure 33. Potential Mission Coverage by ISR Platform

Figure 34 illustrates the predicted time on station for each ISR platform from each base. The RQ-4 with its comparatively high speed and 36 hour mission duration is the clear leader in the ability to remain on-station. Interestingly, the RQ-1 provides the least amount of time on-station per sortie. Despite a 24 hour mission duration, the RQ-4's on-station endurance is limited by its slow speed. It is probable that the ability to cover a greater number of targets per sortie will be more important to overall coverage than the ability to remain on-station for a longer period of time.

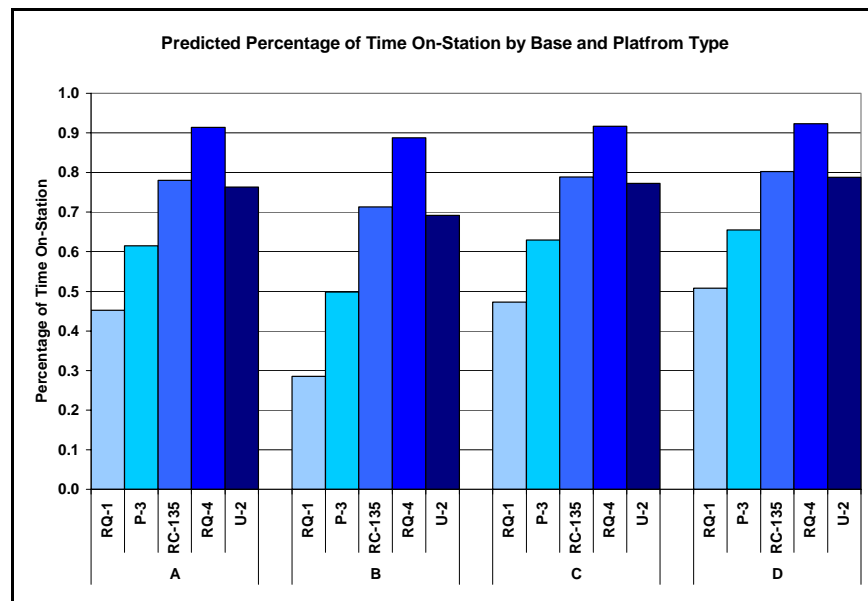


Figure 34. Predicted Percentage of Time On-Station by Base and Platform Type

The ability to satisfy all of the missions in the scenario is shown in Table 9. There are 13 of 20 EO/IR, 7 of 18 SAR, and 4 of 17 SIGINT requirements that cannot be met by any platform. This indicates that only about 44% of the sensor requirements in the non-penetrating scenario can be satisfied. This does not mean that 44% is the maximum coverage number that can be achieved in the simulation. Since ISR platforms receive credit for all missions that are ranged regardless of whether or not they are assigned to that mission, the total coverage number will likely be higher than 44% due to duplication of mission coverage.

EO/IR Sensor Requirements							SAR Sensor Requirements							SIGINT Sensor Requirements						
Mission	RQ-4	RQ-1	P-3	RC-135	U-2	Any	Mission	RQ-4	RQ-1	P-3	RC-135	U-2	Any	Mission	RQ-4	RQ-1	P-3	RC-135	U-2	Any
1.1	***	NO SENSOR REQUIREMENT	***				1.1	***	NO SENSOR REQUIREMENT	***				1.3	2	0	0	2	3	7
2.1	0	0	0	0	0	0	2.1	0	0	0	0	0	0	2.3	1	0	0	1	2	4
3.1	0	0	0	0	0	0	3.1	***	NO SENSOR REQUIREMENT	***				3.3	***	NO SENSOR REQUIREMENT	***			
4.1	1	0	1	0	1	3	4.1	3	3	3	0	3	12	4.3	4	0	0	4	5	13
5.1	0	0	0	0	0	0	5.1	0	0	0	0	0	0	5.3	1	0	0	1	6	8
6.1	0	0	0	0	0	2	6.1	3	3	3	0	4	13	6.3	5	0	0	5	6	16
7.1	***	NO SENSOR REQUIREMENT	***				7.1	***	NO SENSOR REQUIREMENT	***				7.3	5	0	0	5	7	17
8.1	***	NO SENSOR REQUIREMENT	***				8.1	***	NO SENSOR REQUIREMENT	***				8.3	0	0	0	0	0	0
9.1	0	0	0	0	1	1	9.1	3	3	3	0	3	12	9.3	4	0	0	4	6	14
10.1	0	0	0	0	0	0	10.1	1	1	1	0	2	5	10.3	3	0	0	3	7	13
11.1	***	NO SENSOR REQUIREMENT	***				11.1	***	NO SENSOR REQUIREMENT	***				11.3	2	0	0	2	6	10
12.1	0	0	0	0	0	0	12.1	0	0	0	0	2	2	12.3	***	NO SENSOR REQUIREMENT	***			
13.1	0	0	0	0	0	0	13.1	0	0	0	0	0	0	13.3	***	NO SENSOR REQUIREMENT	***			
14.1	1	0	1	0	1	3	14.1	3	3	3	0	4	13	14.3	5	0	0	5	6	16
15.1	0	0	0	0	0	0	15.1	0	0	0	0	0	0	15.3	1	0	0	1	6	8
16.1	0	0	0	0	0	2	16.1	3	3	3	0	4	13	16.3	4	0	0	4	6	14
17.1	0	0	0	0	0	1	17.1	3	3	3	0	4	13	17.3	***	NO SENSOR REQUIREMENT	***			
18.1	0	0	0	0	0	0	18.1	***	NO SENSOR REQUIREMENT	***				18.3	***	NO SENSOR REQUIREMENT	***			
19.1	0	0	0	0	0	0	19.1	3	3	3	0	3	12	19.3	***	NO SENSOR REQUIREMENT	***			
20.1	0	0	0	0	0	0	20.1	2	2	2	0	2	8	20.3	***	NO SENSOR REQUIREMENT	***			
21.1	0	0	0	0	0	1	21.1	1	1	1	0	2	5	21.3	2	0	0	2	4	8
22.1	0	0	0	0	0	0	22.1	0	0	0	0	0	0	22.3	***	NO SENSOR REQUIREMENT	***			
23.1	***	NO SENSOR REQUIREMENT	***				23.1	***	NO SENSOR REQUIREMENT	***				23.3	0	0	0	0	0	0
24.1	0	0	0	0	0	0	24.1	0	0	0	0	0	0	24.3	0	0	0	0	0	0
25.1	0	0	0	0	0	0	25.1	0	0	0	0	0	0	25.3	0	0	0	0	0	0

Table 9. Non-Penetrating Scenario: Ability to Satisfy Sensor Requirements by Platform Type (Cells highlighted in red indicate that the sensor requirement cannot be met by any platform type)

### c. Assessment

The following assessments are made based on the preceding analysis of the factors affecting the non-penetrating scenario:

- The U-2's ability to cover the most missions per sortie coupled with its relatively high speed will make it the most significant asset in the simulation.
- The RQ-4 will be important in maximizing coverage due to its long mission duration and relatively strong sensor package.
- The relatively long range of the SIGINT sensor and the second best on-station performance may make the RC-135 a significant contributor to overall coverage.
- The P-3's relatively short sensor ranges and the lack of a SIGINT sensor will limit its contribution to mission coverage.
- It is expected that the inability to cover any EO/IR targets will limit the utilization of the RQ-1 within the simulation.
- The collective inability to range over 50% of the missions will severely limit the mean coverage.

## 2. Penetrating Scenario

The penetrating scenario allows the violation of the COI's airspace, removing the standoff limitation and adding 12 additional mission areas. Waypoint routing is no longer used; however, the ISR platforms are now vulnerable to air defense threats.

### a. Scenario Geometry

As shown in Chapter III, Table 1, there are 25 targets, each with up to 3 sensor requirements. These 25 targets are broken down into 20 EO/IR, 18 SAR, and 17 SIGINT requirements, for a total of 55 missions. These 55 missions or sensor requirements can be serviced from any of the 26 mission areas in the penetrating scenario. (*Satisfaction of sensor requirements depends upon the availability an ISR platform with the correct sensor package, sufficient sensor range and the platform's ability to meet the minimum altitude to achieve line-of-sight.*) By matching the 26 mission areas with the 55 missions, 1430 possible mission area-to-mission pairings are possible; 520 EO/IR, 468 SAR, and 442 SIGINT. See Figure 26, page 65 for an example of mission area-to-mission matching. Each of these pairings is taken into account by JDAFS in determining the optimum allocation of ISR platforms.

Just as in the non-penetrating scenario, it is expected that the lowest absolute distance and the lowest mean and median distance from a base to its associated mission areas will play a significant role in determining the overall coverage achieved by the various ISR platforms. An examination of the basing configuration as shown in Figure 35 and Table 10 reveals the following:

- Base D is closest to its nearest mission area, then A, C, and B, respectively.
- Base D has the lowest maximum distance to its farthest mission area, then A, C, and B, respectively.
- Base D has the lowest mean and median travel distance to its mission areas, then A, C, and B, respectively.

Since no waypoint routing is necessary, the relative distances are constant from each base to its mission areas. That is, not only is Base D the closest to its nearest mission area, it also has the lowest mean distance to its mission areas.

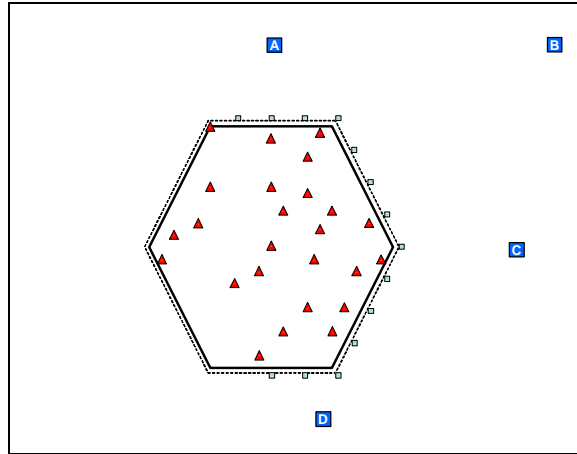


Figure 35. Basing Configuration

SUMMARY OF BASE TO MISSION AREA DISTANCE STATISTICS				
	A	B	C	D
MIN	328000	936862	578000	187840
MAX	1398315	1790219	1500000	1268418
MEAN	877152	1345442	1018558	764431
MEDIAN	901274	1336872	1036622	776566
All distances are in meters				

Table 10. Penetrating Scenario Summary of Base to Mission Area Distance Statistics

***b. Sensor Coverage***

Each of the ISR platforms has a differing ability meet the various sensors demands. The requirement to collect from standoff mission areas in the non-penetrating scenario limits the amount of coverage each aircraft can provide. The following figures depict the potential coverage by each type of platform and sensor.<sup>15</sup>

Figure 36 illustrates the potential coverage by the RQ-1 EO/IR and SAR sensors. There are 3 EO/IR targets and 18 SAR targets that can be ranged by the RQ-1. Note that the RQ-1 can provide SAR coverage of the entire COI with the exception of a small area in the southwest corner.

<sup>15</sup> Note that the amount of coverage depicted in the illustrations may differ slightly from the amount of coverage that has been calculated due to the imprecise nature of the graphics. In all cases, the text refers to the calculated coverage.

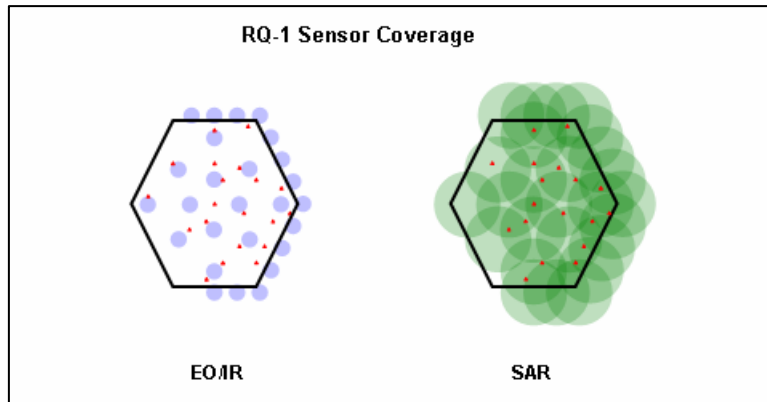


Figure 36. RQ-1 Sensor Coverage for the Penetrating Scenario

Figure 37 demonstrates the ability of the RQ-4 to cover EO/IR, SAR and SIGINT sensor requirements. The RQ-4 can satisfy 13 EO/IR, 18 SAR, and 17 SIGINT requirements. The RQ-1 can provide SAR coverage of the entire COI with the exception of a small area in the southwest corner and SIGINT coverage of the whole country.

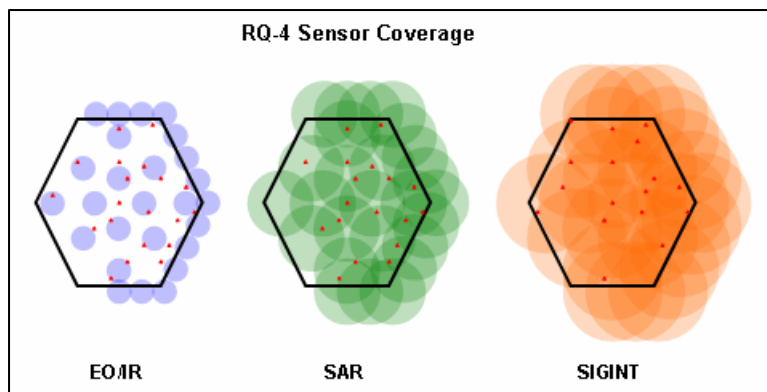


Figure 37. RQ-4 Sensor Coverage for the Penetrating Scenario

The ability of the P-3 to provide EO/IR and SAR coverage is illustrated in Figure 38. The P-3 can range 13 EO/IR missions and 18 SAR missions. Like the RQ-1 and RQ-4, the P-3 can range all but a small portion of the country with its SAR sensor.

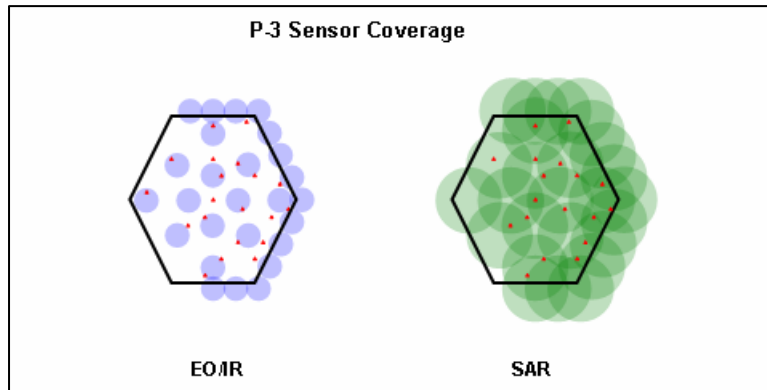


Figure 38. P-3 Sensor Coverage for the Penetrating Scenario

Figure 39 depicts the coverage of the RC-135. The RC-135 has the ability to meet all 17 SIGINT sensor requirements and can cover the entire country.

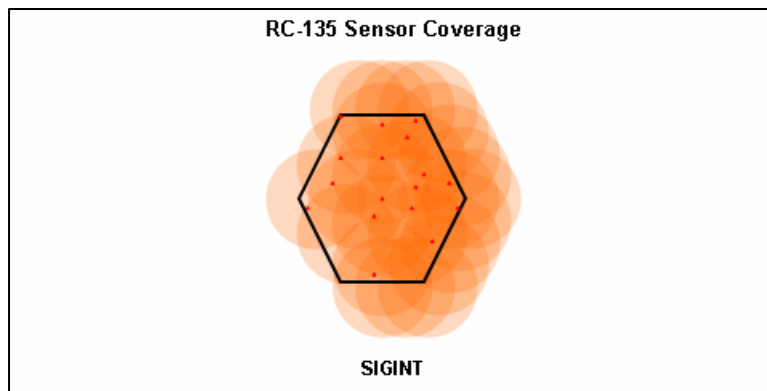


Figure 39. RC-135 Sensor Coverage for the Penetrating Scenario

The U-2's sensor capabilities are shown in Figure 40. The U-2 can satisfy 17 EO/IR, 18 SAR, and 17 SIGINT missions. The SAR and SIGINT sensor packages on the U-2 can range any location in the COI. Just as in the non-penetrating scenario, the U-2 is the most capable platform, sensor wise.

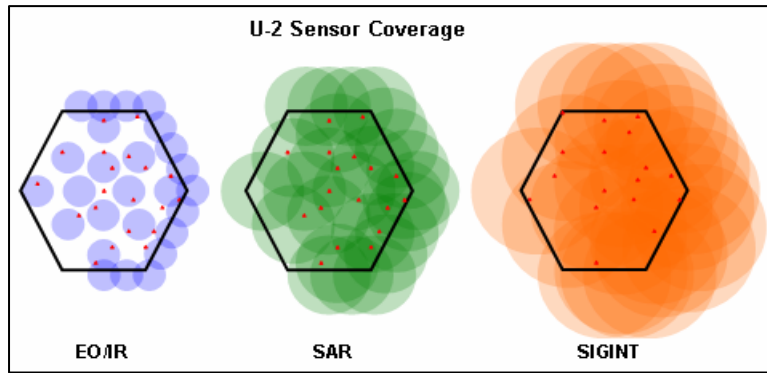


Figure 40. U-2 Sensor Coverage for the Penetrating Scenario

Table 11 provides a summary of the number of missions that can be covered by each ISR platform from each mission area. Ranked by ability to provide coverage of the most targets per mission area, the most capable aircraft is the U-2, followed by the RQ-4, the RC-135, the P-3, and finally the RQ-1. This further demonstrates the U-2's superior ability to provide coverage. Note that the capability of the RQ-1 and the P-3 is very similar, with the P-3 marginally exceeding the RQ-1.

MISSION AREA	RQ-4				RQ-1			P-3			RC-135	U-2			
	EO/IR	SAR	SIGINT	TOTAL	EO/IR	SAR	TOTAL	EO/IR	SAR	TOTAL	SIGINT/TOTAL	EO/IR	SAR	SIGINT	TOTAL
1	1	1	5	7	0	1	1	1	1	2	5	1	2	6	9
2	0	2	3	5	0	2	2	0	2	2	3	1	2	6	9
3	0	1	3	4	0	1	1	0	1	1	3	1	1	5	7
4	0	1	4	5	0	1	1	0	1	1	4	0	2	7	9
5	0	2	5	7	0	2	2	0	2	2	5	0	3	8	11
6	1	2	4	7	0	2	2	1	2	3	4	1	3	6	10
7	0	3	2	5	0	3	3	0	3	3	2	1	3	6	10
8	0	3	4	7	0	3	3	0	3	3	4	1	4	6	11
9	0	3	2	5	0	3	3	0	3	3	2	1	4	5	10
10	0	2	1	3	0	2	2	0	2	2	1	1	2	4	7
11	0	1	1	2	0	1	1	0	1	1	1	0	1	2	3
12	0	1	1	2	0	1	1	0	1	1	1	0	3	2	5
13	0	2	1	3	0	2	2	0	2	2	1	1	2	1	4
24	0	1	3	4	0	1	1	0	1	1	3	0	1	6	7
51	1	2	6	9	1	2	3	1	2	3	6	1	4	8	13
52	1	1	5	7	0	1	1	1	1	2	5	1	2	9	12
53	2	3	8	13	0	3	3	2	3	5	8	2	5	10	17
54	1	4	8	13	1	4	5	1	4	5	8	1	4	11	16
55	1	0	3	4	1	0	1	1	0	1	3	1	0	4	5
56	0	3	5	8	0	3	3	0	3	3	5	0	3	8	11
57	1	4	8	13	0	4	4	1	4	5	8	1	7	10	18
58	1	3	6	10	0	3	3	1	3	4	6	1	5	6	12
59	1	3	3	7	0	3	3	1	3	4	3	1	5	8	14
60	0	2	4	6	0	2	2	0	2	2	4	1	2	5	8
61	1	4	6	11	0	4	4	1	4	5	6	2	5	9	16
62	2	2	1	5	0	2	2	2	2	4	1	2	2	4	8
TOTAL	14	56	102	172	3	56	59	14	56	70	102	23	77	162	262
MIN	0	0	1	3	0	0	1	0	0	1	1	0	0	1	4
MAX	2	4	8	13	1	4	5	2	4	5	8	2	7	11	18
MEAN	0.9	2.4	4.8	8.1	0.2	2.4	2.6	0.9	2.4	3.3	4.8	1.1	3.4	7.1	11.5
MEDIAN	1	2.5	5	7.5	0	2.5	3	1	2.5	3.5	5	1	3.5	8	12

Table 11. Penetrating Scenario: Number of Missions Potentially Satisfied from Each Mission Area by Platform and Sensor Type



Figure 41 compares the ability of the various ISR platforms to provide coverage. Note that the U-2 is superior to all other aircraft in every category. This difference is due to the U-2's advantage in sensor range for all types of sensors.

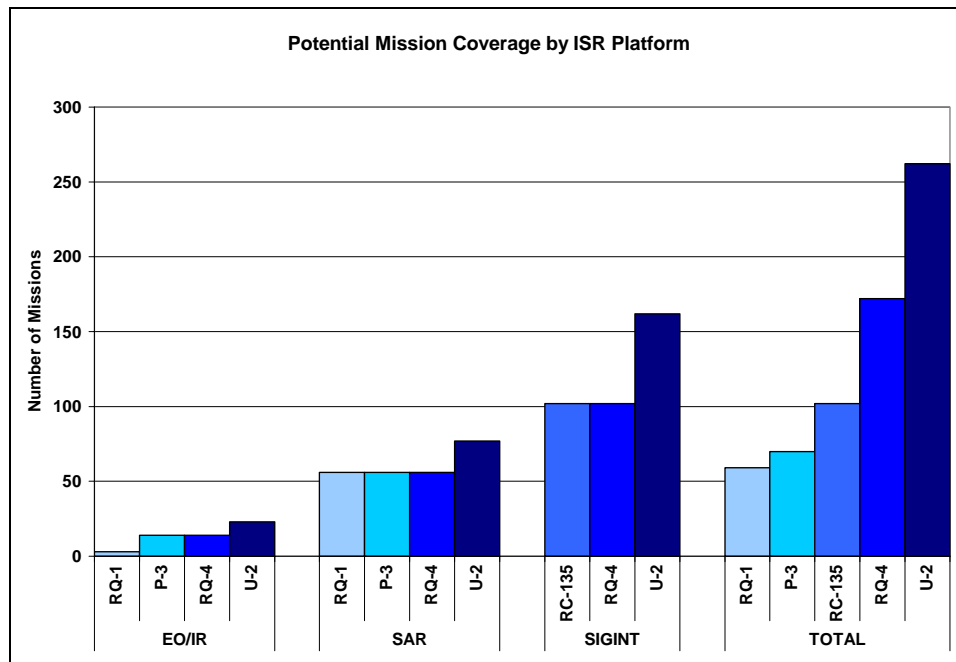


Figure 41. Potential Mission Coverage by ISR Platform

Figure 42 illustrates the predicted time on station for each ISR platform from each base. The RQ-4 with its comparatively high speed and 36 hour mission duration is the clear leader in the ability to remain on-station. Interestingly, the RQ-1 provides the least amount of time on-station per sortie. Despite a 24 hour mission duration, the RQ-4's on-station endurance is limited by its slow speed. The percentage of time on-station increases slightly for platforms at Bases A and D and decreases slightly for aircraft at Bases B and C when compared to the non-penetrating scenario due to the removal of waypoint routing. As in the non-penetrating scenario, it is anticipated that the ability to cover a greater number of targets per sortie will be more important to overall coverage than the ability to remain on-station for a longer period of time.

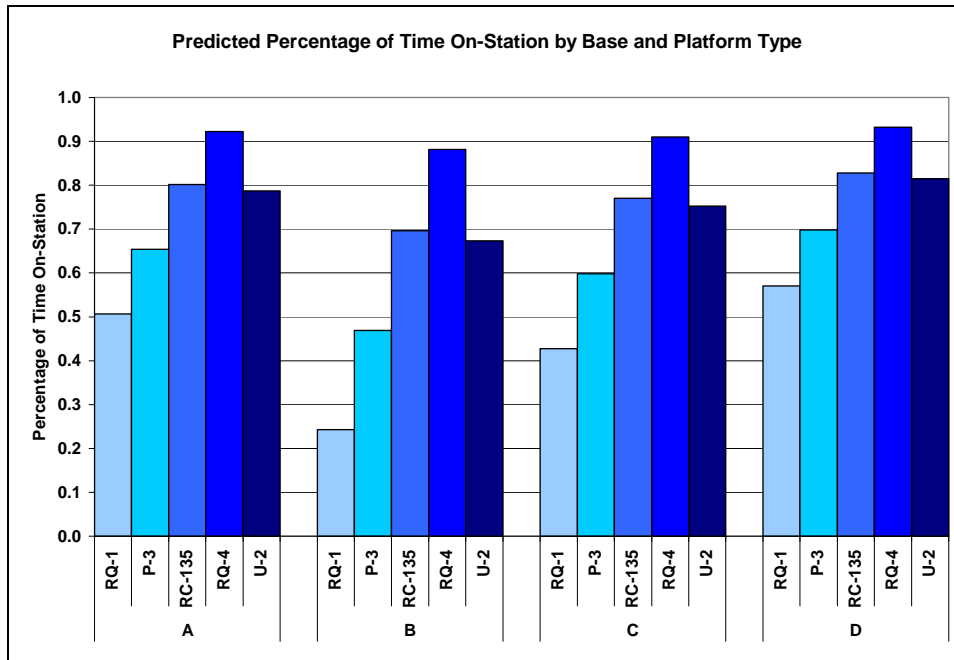


Figure 42. Predicted Percentage of Time On-Station by Base and Platform Type

The ability to satisfy all of the missions in the scenario is shown in Table 12. There are 17 of 20 EO/IR, 18 of 18 SAR, and 17 of 17 SIGINT requirements that can be met. This indicates that approximately 95% of the sensor requirements in the scenario can be satisfied by the available platforms. This does not mean, however, that 95% is the amount of coverage that will be achieved in a simulation. The effects of transit time, attrition, and platform on-station time, among other factors will keep the total coverage from reaching 95%.

EO/IR Sensor Requirements							SAR Sensor Requirements							SIGINT Sensor Requirements								
Mission	RQ-4	RQ-1	P-3	RC-135	U-2	Any	Mission	RQ-4	RQ-1	P-3	RC-135	U-2	Any	Mission	RQ-4	RQ-1	P-3	RC-135	U-2	Any		
1.1	*** NO SENSOR REQUIREMENT ***						1.1	*** NO SENSOR REQUIREMENT ***						1.3	4	0	0	4	5	13		
2.1	1	0	1		0	1	3	2.1	1	1	1		0	1	4			6	7	19		
3.1	1	1	1		0	1	4	3.1	*** NO SENSOR REQUIREMENT ***						3.3	*** NO SENSOR REQUIREMENT ***						
4.1	2	1	2		0	2	7	4.1	4	4	4		0	4	16	4.3	5	0	0	5	9	19
5.1	0	0	0		0	0	0	5.1	2	2	2		0	4	10	5.3	7	0	0	7	12	26
6.1	0	0	0		0	2	2	6.1	3	3	3		0	5	14	6.3	7	0	0	7	9	23
7.1	*** NO SENSOR REQUIREMENT ***						7.1	*** NO SENSOR REQUIREMENT ***						7.3	8	0	0		8	12	28	
8.1	*** NO SENSOR REQUIREMENT ***						8.1	*** NO SENSOR REQUIREMENT ***						8.3	3	0	0		3	6	12	
9.1	0	0	0		0	2	2	9.1	4	4	4		0	4	16	9.3	7	0	0	7	11	25
10.1	1	0	1		0	1	3	10.1	3	3	3		0	5	14	10.3	7	0	0	7	14	28
11.1	*** NO SENSOR REQUIREMENT ***						11.1	*** NO SENSOR REQUIREMENT ***						11.3	7	0	0		7	14	28	
12.1	1	0	1		0	1	3	12.1	2	2	2		0	6	12	12.3	*** NO SENSOR REQUIREMENT ***					
13.1	0	0	0		0	1	1	13.1	3	3	3		0	3	12	13.3	*** NO SENSOR REQUIREMENT ***					
14.1	1	0	1		0	1	3	14.1	4	4	4		0	6	18	14.3	8	0	0	8	10	26
15.1	1	0	1		0	1	3	15.1	2	2	2		0	4	10	15.3	7	0	0	7	14	28
16.1	1	0	1		0	3	5	16.1	4	4	4		0	5	17	16.3	6	0	0	6	10	22
17.1	0	0	0		0	1	1	17.1	4	4	4		0	5	17	17.3	*** NO SENSOR REQUIREMENT ***					
18.1	1	0	1		0	1	3	18.1	*** NO SENSOR REQUIREMENT ***						18.3	*** NO SENSOR REQUIREMENT ***						
19.1	0	0	0		0	0	0	19.1	5	5	5		0	6	21	19.3	*** NO SENSOR REQUIREMENT ***					
20.1	1	0	1		0	1	3	20.1	3	3	3		0	5	14	20.3	*** NO SENSOR REQUIREMENT ***					
21.1	1	0	1		0	2	4	21.1	2	2	2		0	3	9	21.3	4	0	0	4	8	16
22.1	1	1	1		0	1	4	22.1	3	3	3		0	3	12	22.3	*** NO SENSOR REQUIREMENT ***					
23.1	*** NO SENSOR REQUIREMENT ***						23.1	*** NO SENSOR REQUIREMENT ***						23.3	2	0	0		2	4	8	
24.1	1	0	1		0	1	3	24.1	3	3	3		0	4	13	24.3	6	0	0	6	9	21
25.1	0	0	0		0	0	0	25.1	4	4	4		0	4	16	25.3	8	0	0	8	8	24

Table 12. Penetrating Scenario: Ability to Satisfy Sensor Requirements by Platform Type (Cells highlighted in red indicate that the sensor requirement cannot be met by any platform type)

### c. Assessment

The following assessments are made based on the preceding analysis of the factors affecting the penetrating scenario:

- The U-2's ability to cover the most missions per sortie coupled with its relatively high speed will make it the most significant asset in the simulation.
- The RQ-4 will be important in maximizing coverage due to its long mission duration and relatively strong sensor package.
- The relatively long range of the SIGINT sensor and the second best on-station performance may make the RC-135 a significant contributor to overall coverage.
- The P-3's relatively short sensor ranges and the lack of a SIGINT sensor will limit its contribution to mission coverage.
- It is expected that the minimal ability to cover EO/IR targets, along with the lack of a SIGINT sensor, will limit the utilization of the RQ-1 within the simulation.
- The fact that 95% of the sensor requirements can be met by the available platforms will dramatically improve coverage compared to the non-penetrating scenario.

## C. MEASURES OF EFFECTIVENESS (MOE)

The JDAFS simulation provides for the generation of a number of MOEs including, Coverage, Coverage by Type, and Attrition.

### 1. Non-Penetrating Scenario Coverage

#### a. Coverage Regression Model

An initial plot of the distribution and summary statistics for 274 design points in the non-penetrating scenario is shown in Figure 43. The coverage results appear to be roughly normally distributed with a mean of 0.48. The five outlying data points at the bottom of the outlier box plot warrant further examination.

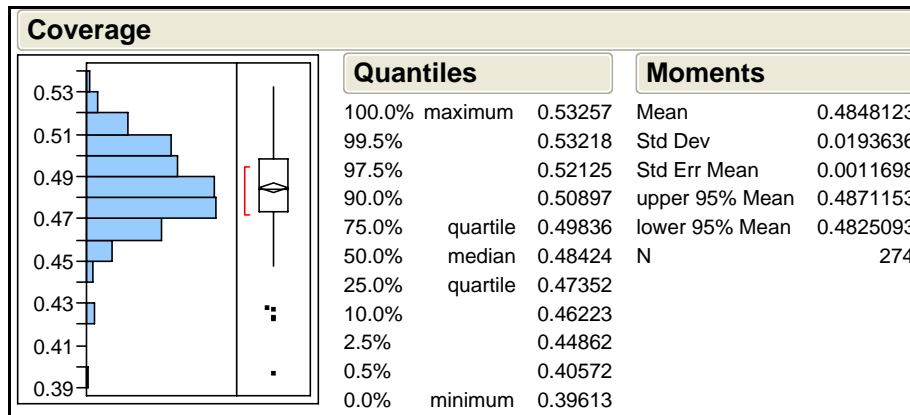


Figure 43. Distribution and Summary Statistics of Mission Area Coverage

An examination of the data reveals that four of the outlying data points 1, 2, 4, and 265 are the result of design points having only a single base available for operations (See Table 13). Even though each operating location had a full compliment of aircraft (21 total airframes), the mean coverage ranked at the bottom of all the results. When ranked from greatest to least coverage, D, C, A, then B, this ordering is not surprising when compared to the mean distance of the bases to their mission areas in the pre-simulation analysis. Having a single operating base available to ISR platforms in a region of the size encompassed in this study is unrealistic. Therefore, the design points that include only one operating location will not be considered for the remainder of this

analysis. The remaining outlier, data point 70, had ISR platforms at all locations (30 total airframes); however, having only one U-2 and a near maximum optimization interval appear to be the reason for the low mean coverage. There is no easy or obvious justification for removing this design point from the data set for further analysis.

Design Point	A RQ-4	A RQ-1	A P-3	A RC-135	A U-2	B RQ-4	B RQ-1	B P-3	B RC-135	B U-2	C RQ-4	C RQ-1	C P-3	C RC-135	C U-2	D RQ-4	D RQ-1	D P-3	D RC-135	D U-2	OPT INT	Coverage
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	6	3	3	3.25	0.4270
2	0	0	0	0	0	0	0	0	0	0	3	6	6	3	3	0	0	0	0	0	3.25	0.4226
4	0	0	0	0	0	3	6	6	3	3	0	0	0	0	0	0	0	0	0	0	3.25	0.3961
70	1	2	0	1	0	3	3	2	1	1	0	4	3	1	0	1	4	3	0	0	5.92	0.4267
265	3	6	6	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.25	0.4217

Table 13. Non-Penetrating Scenario: Low Outlying Data Points

For comparison with future models, a full quadratic model with the outlying data points was constructed. Figure 44 shows this model. Note that the R-squared<sup>16</sup> value for this model is 0.73.

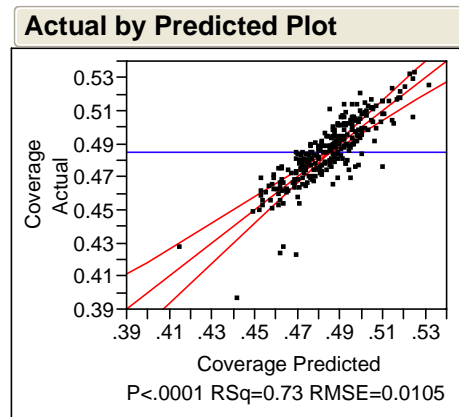


Figure 44. Actual by Predicted Coverage Plot for Full Quadratic Model with Single Base Outliers Included.

After removing the single base outliers, the distribution and summary statistics for the non-penetrating scenario data were recalculated. The increase in the mean coverage is negligible, but the remaining data more closely approximates a normal distribution (See Figure 45).

<sup>16</sup>  $R^2$  or R-squared, the coefficient of determination, is defined as the proportion of response variation that is explained by the regression model (Devore 2004, 514).

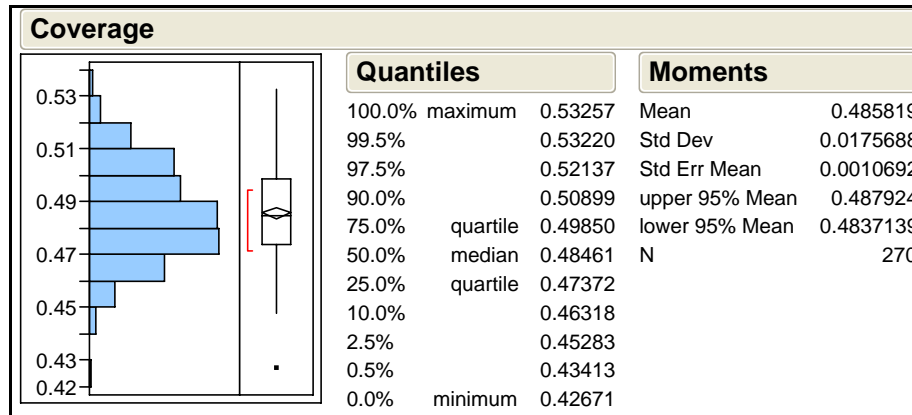


Figure 45. Non-Penetrating Scenario: Distribution and Summary Statistics of Mission Area Coverage (*single base outliers removed*)

From the final 270 design point dataset a full quadratic model with main effect, interaction, and polynomial terms was created. The Stepwise Regression Control settings within JMP were as follows:

- Probability to enter: 0.01
- Probability to leave: 0.01
- Direction: Mixed

The Construct Model Effects macros for Factorial to Degree and Polynomial to Degree were set at 2 to allow two-way interaction and quadratic terms.

The resultant model Achieves an R-squared of 0.78 and contains 12 main effect terms, 4 interaction terms, and 3 second order terms. See Figures 46 and 47 for the regression plot and a list of the regression model terms.

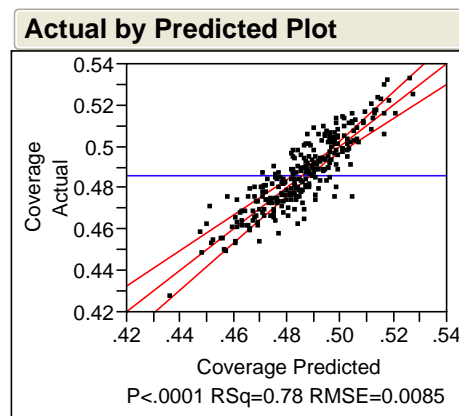


Figure 46. Actual by Predicted Coverage Plot for Full Quadratic Model with Single Base Outliers Removed

Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.4762323	0.002843	167.51	<.0001*
A RQ-4	-0.002767	0.000534	-5.18	<.0001*
A RQ-1	-0.000885	0.000285	-3.10	0.0021*
A RC-135	0.0039884	0.000535	7.45	<.0001*
A U-2	0.0056309	0.000536	10.50	<.0001*
B RQ-4	-0.002767	0.000541	-5.12	<.0001*
B RC-135	-0.000835	0.000538	-1.55	0.1219
B U-2	0.0035851	0.000534	6.71	<.0001*
C RQ-4	-0.002511	0.000531	-4.73	<.0001*
C U-2	0.0058404	0.000531	10.99	<.0001*
D RQ-4	-0.001957	0.000529	-3.70	0.0003*
D U-2	0.0074843	0.000532	14.07	<.0001*
OPT INT	-0.004388	0.000361	-12.15	<.0001*
(A RQ-4-1.52963)*(B RC-135-1.52963)	-0.002434	0.000522	-4.66	<.0001*
(A RC-135-1.52963)*(D RQ-4-1.52963)	-0.001769	0.000518	-3.41	0.0007*
(B RC-135-1.52963)*(D RQ-4-1.52963)	-0.001793	0.000535	-3.35	0.0009*
(C RQ-4-1.52963)*(D U-2-1.52963)	-0.002549	0.000504	-5.05	<.0001*
(B RQ-4-1.52963)*(B RQ-4-1.52963)	0.001986	0.000574	3.46	0.0006*
(C U-2-1.52963)*(C U-2-1.52963)	-0.001624	0.00057	-2.85	0.0047*
(D RQ-4-1.52963)*(D RQ-4-1.52963)	0.0030399	0.000559	5.44	<.0001*

Figure 47. Full Quadratic Coverage Model Terms

As expected, the most capable platforms, the U-2 and RQ-4, show up as terms from each base. The RC-135 is reflected twice from Bases A and B. The RQ-1 from Base A is the only entry for that platform. Interestingly, the P-3 is not represented in the model at all. In addition to the aircraft factors, the optimization interval term is also included in the final model.

To test the validity of the Coverage Full Quadratic Regression model, the regression assumptions from Part A of this chapter must be verified. The Actual by Predicted Plot in Figure 46 indicates that the relationship between the response variable (coverage) and the regressors is reasonably linear. The apparently random cloud of data points with a mean of zero in the Residual by Predicted Plot, Figure 48, confirms that the requirements for a zero mean, constant variance, and lack of correlation of the residuals is met. Compliance with the normality assumption is shown in Figure 49 by a histogram of the residuals overlaid with a normal curve and a normal quantile plot.

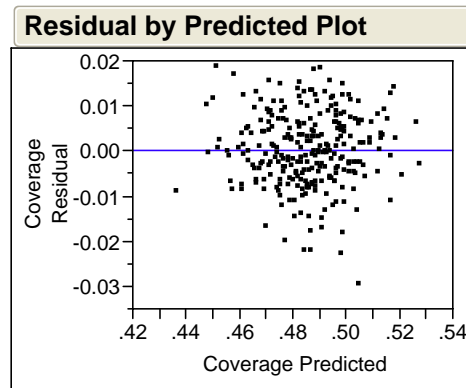


Figure 48. Residual by Predicted Plot for Coverage Model

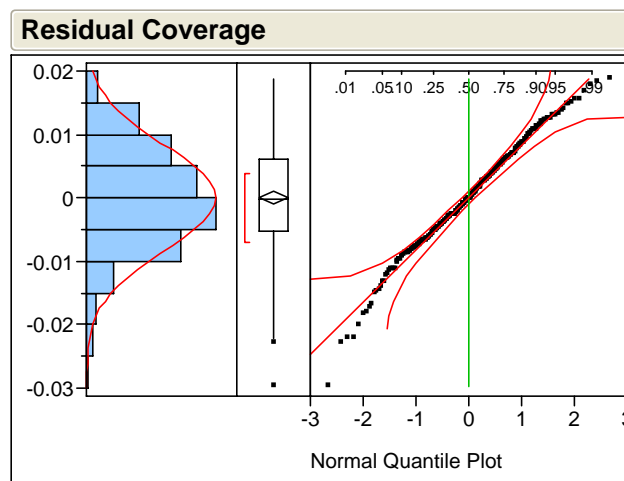


Figure 49. Histogram and Normal Quantile Plot of Residuals for Coverage Model

### ***b. Coverage Factor Interactions***

To further examine the interactions of the factors in the model, an Interaction Profile Plot, Figure 50, was constructed. Each of the individual cells within the larger plot display the interaction between two factors and their effect on Coverage. Each cell contains the plot of two lines, one for the high setting and one for the low setting of the term found in the name box for that row. Solid lines or curves indicate the presence of interaction between terms. The lighter, broken lines or curves indicate no interaction. Note that the lines without interaction are nearly parallel. The y axis of the grid is the response variable, coverage, and the x axis indicates the levels for each factor. When assessing the change to the response variable based on moving along one of the lines in a single cell, it is assumed that all other factors are held constant.



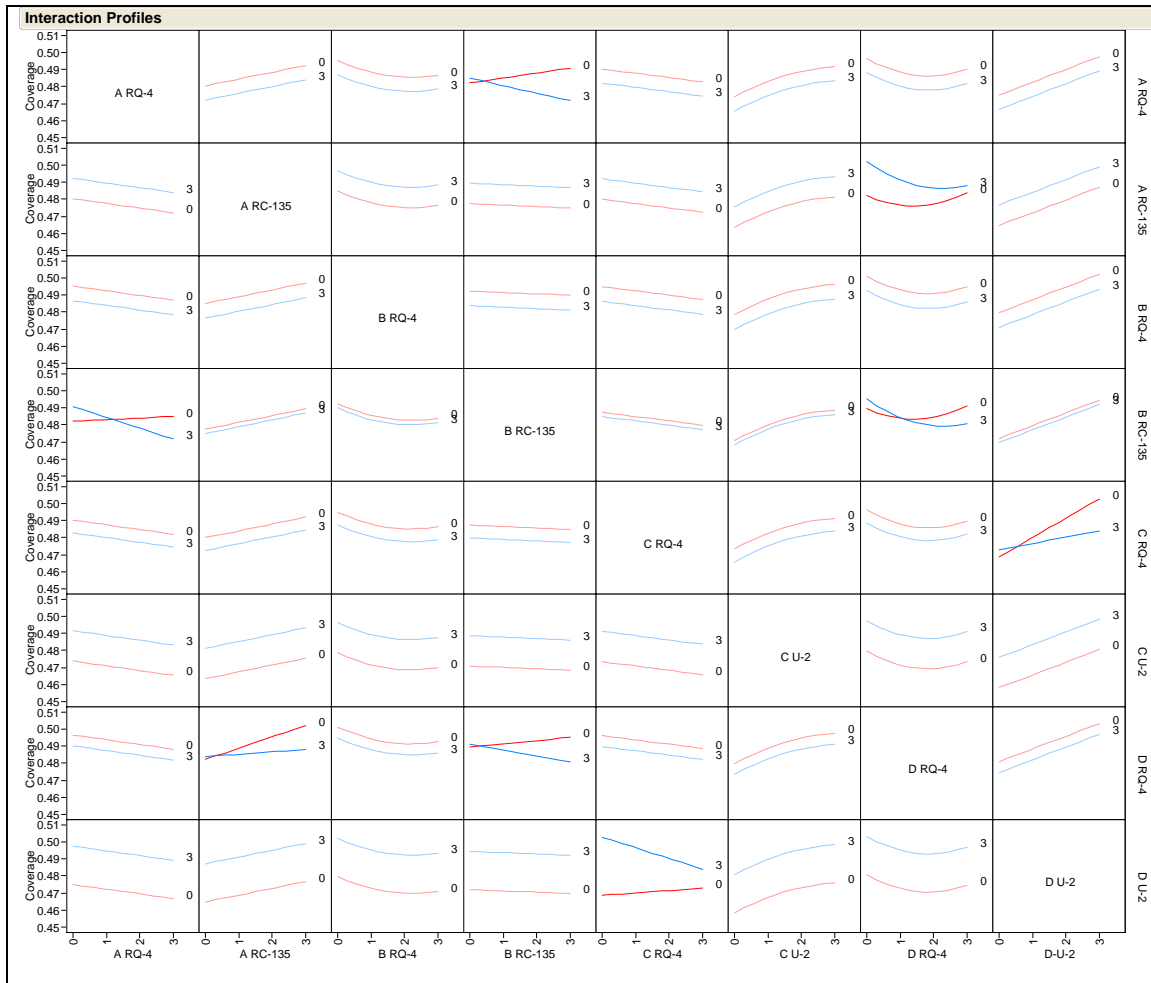


Figure 50. Interaction Profile for Final Coverage Model

The following figures displaying terms with significant interaction are taken from the larger Interaction Profile plot, Figure 50. Note that in all cases, the coverage varies only marginally regardless of the settings of the interaction terms for this model.

- Figure 51 shows that with no RQ-4s at Base A, total coverage actually increases with the addition of RC-135s at Base B. However, if there are 3 RQ-4s at Base A, coverage declines as RC-135s are added at Base B.

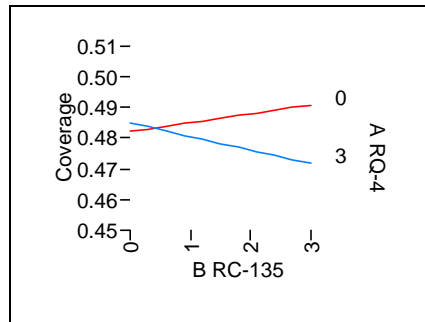


Figure 51. Interaction Profile for A RQ-4 and B RC-135

- Figure 52 shows that the RC-135s at Base A have a quadratic interaction with the addition of RQ-4s at Base D. That is, regardless of the number of RC-135s at Base A, coverage initially declines and then rises with the addition of RQ-4s at Base D.

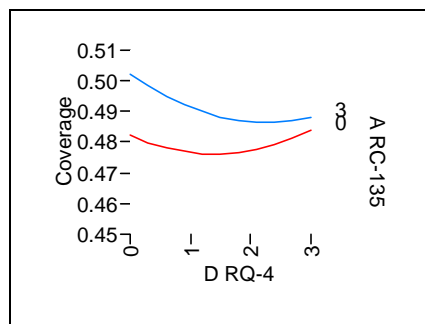


Figure 52. Interaction Profile for A RC-135 and D RQ-4

- Figure 53 shows that with no RC-135s at Base B, total coverage actually increases slightly with the addition of RQ-4s at Base A. However, if there are 3 RC-135s at Base B, coverage declines as RQ-4s are added at Base A.

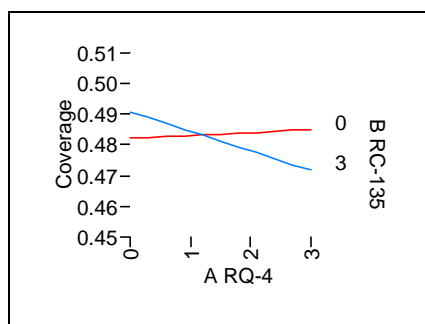


Figure 53. Interaction Profile for B RC-135 and A RQ-4

- Figure 54 shows that the RC-135s at Base B have a quadratic interaction with the addition of RQ-4s at Base D. That is, regardless of the number of RC-135s at Base B, coverage initially declines and then rises with the addition of RQ-4s at Base D.

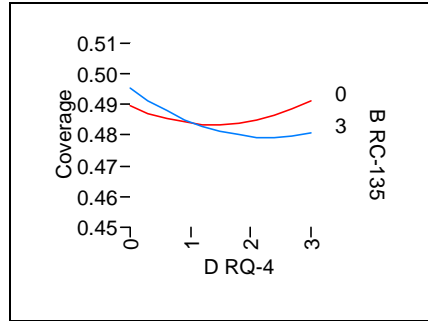


Figure 54. Interaction Profile for B RC-135 and D RQ-4

- Figure 55 shows that with the number of RQ-4s at Base C at zero or three, total coverage increases with the addition of U-2s at Base D. The slope of the line for zero RQ-4s is steeper, indicating that it is better to have no RQ-4's at Base C than to have the maximum number.

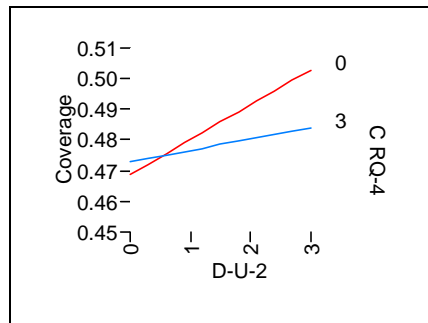


Figure 55. Interaction Profile for C RQ-4 and D U-2

- Figure 56 shows that with the number of RQ-4s at Base D at zero or three, total coverage increases with the addition of RC-135s at Base A. The slope of the line for zero RQ-4s is steeper, indicating that it is better to have no RQ-4's at Base D than to have the maximum number.

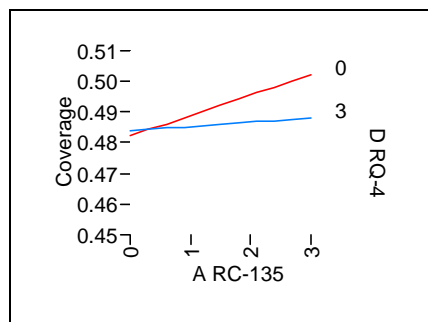


Figure 56. Interaction Profile for D RQ-4 and A RC-135

- Figure 57 shows that with no RQ-4s at Base D, total coverage actually increases with the addition of RC-135s at base B. However, if there are 3 RQ-4s at Base D, coverage declines as RC-135s are added at Base B.

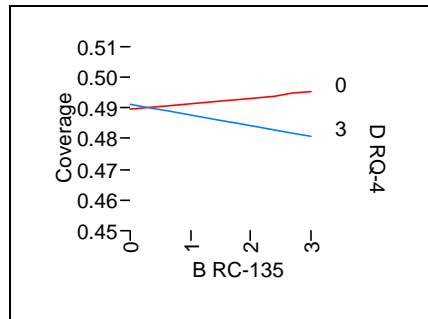


Figure 57. Interaction Profile for D RQ-4 and B RC-135

- Figure 58 shows that with no U-2s at Base D, total coverage increases slightly with the addition of RQ-4s at Base C. However, if there are 3 U-2s at Base D, coverage declines as RQ-4s are added at Base C.

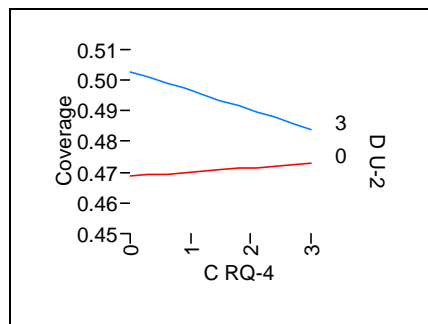


Figure 58. Interaction Profile for D U-2 and C RQ-4

In several of the cases illustrated above, coverage actually declines with addition of more aircraft. This is counter intuitive. Normally, the expectation is that more assets provide more coverage. The seeming anomaly is explained by the optimization that takes place within JDAFS. The optimization algorithm finds the best coverage possible based on matching the assets available to the missions to be serviced. In the simulation, only one platform can be assigned to a mission. Once that assignment is made no additional aircraft can be assigned to the same missions. The addition of more aircraft can result in inferior platforms being assigned to missions, thereby preventing more capable aircraft from having the opportunity for maximum assignment.

*c. Coverage Regression Tree Analysis*

Another means of exploring the data and confirming the validity of the regression model is through the use of classification and regression trees (CART). To determine the number of splits that would continue to yield additional explanatory value for Coverage, 20 splits were done in rapid succession to record the R-squared value without regard to the content or structure of the regression tree. These R-squared values were plotted to find the point that the curve began to plateau, indicating diminishing returns from each successive split. In this case, 11 splits are warranted. Figure 59 provides a plot of the R-squared values against the number of splits.

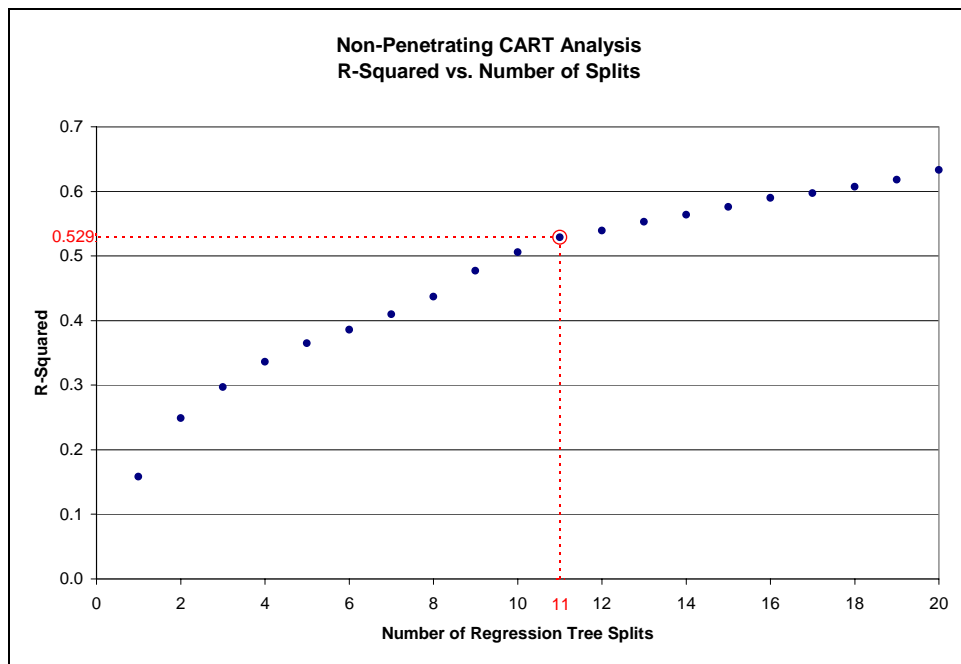


Figure 59. R-Squared vs. Number of Regression Tree Splits

Figure 60 shows the regression tree for Coverage with 11 splits. The full tree and partition graph can be found in Appendix I. The first split indicates that better coverage is obtained when the optimization interval is 4.64 hours or less. The second and third splits are on the presence of U-2s. In the second split, coverage is improved by having two or more U-2s at Base D and in the third split coverage is improved by having

at least one U-2 at Base C. The fourth split indicates that better coverage is gained by having at least one RQ-4 at Base B. The fifth split continues to demonstrate the importance of the U-2, showing that it is beneficial to have two or more U-2s at Base A. The sixth split indicates that coverage is improved by the stationing at least one RC-135 at Base A. The seventh split indicates that no RQ-4 platforms at Base A improves coverage. The eighth split is a return to the optimization interval, showing that coverage improves with optimization intervals of 3.03 hours or less. The most significant factor at the ninth split is U-2s at Base A, indicating that coverage is improved by having at least one U-2 at Base A. Split ten indicates improved coverage by stationing one or more RC-135s at Base A. The final split again is on U-2s at Base A, this time indicating improved coverage with one or more U-2s at Base A.

The splits in the regression tree, especially the multiple splits on optimization interval, Base A U-2s, and the split on Base D U-2s, serve to reinforce the findings from the regression model.

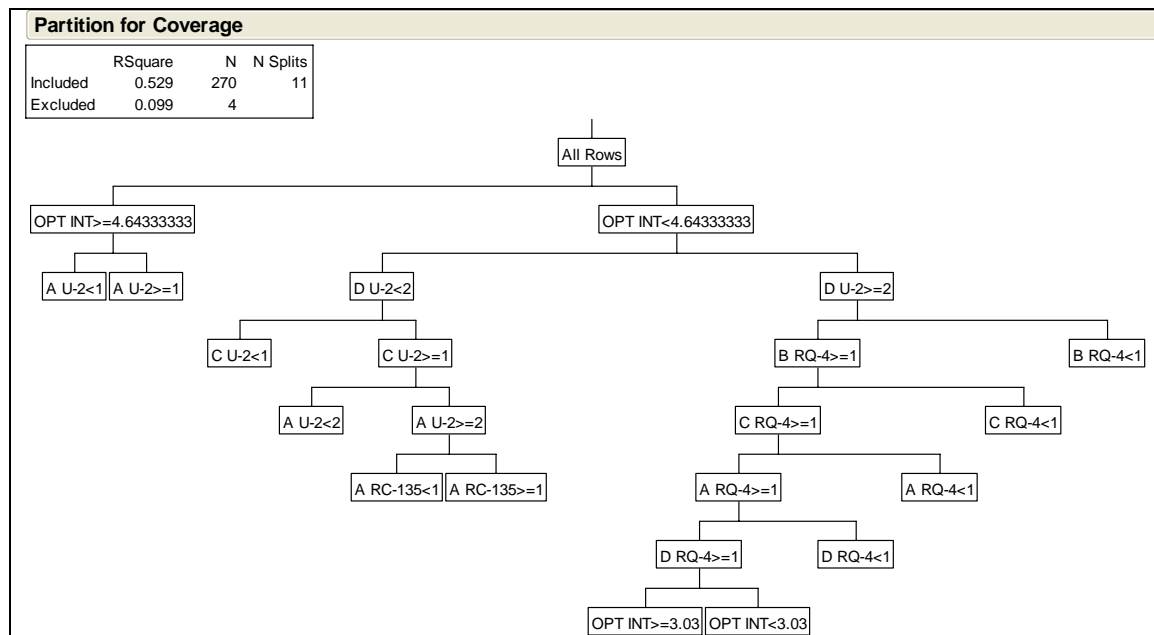


Figure 60. Regression Tree for Coverage

**d. Coverage Contour Plot Analysis**

To further explore the significance of the U-2 as a primary driver of the level of Coverage in the non-penetrating regression model, a contour plot was generated to illustrate the how the number of U-2s relates to the total number of aircraft. The various color filled regions of the plot represent the amount of coverage attained as the number of U-2s and total aircraft vary. The combinatorial nature of the problem and strong interactions of the regressors, coupled with the fact that the other factors are not held fixed, results in a non-smooth contour plot. Additionally, the combinatorial nature and base locations along with the approximate dynamic programming technique cause “islands” in the contour plot. The contour plot is read by selecting a value on the *x*-axis, TOTAL ACFT, and then examining the corresponding coverage based on number of U-2 platforms on the *y*-axis (i.e., given 30 total aircraft, as the number of U-2 platforms ranges between 1 and 9, coverage ranges from  $\leq 48.3\%$  to  $> 50\%$ ). Figure 61 demonstrates that in nearly all cases, coverage is improved by increasing the number of U-2 platforms. It appears that having three or less U-2’s dramatically limits the level of coverage while six or more tends to drive coverage up. The value of additional U-2 assets peaks at 11.

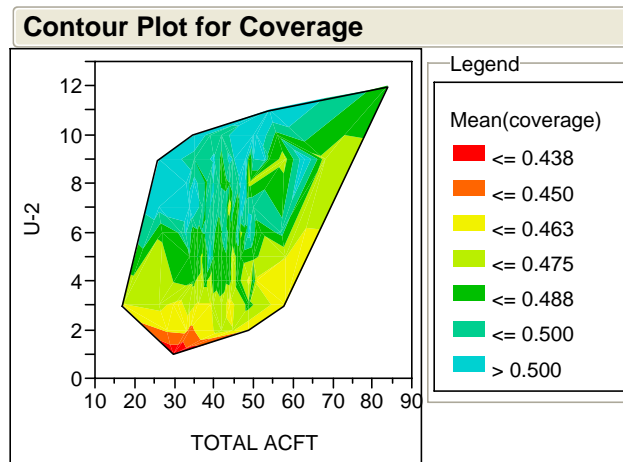


Figure 61. Coverage Contour Plot of Coverage for U-2 vs. Total Aircraft

## 2. Non-Penetrating Scenario Coverage by Type

The coverage by type MOE is a subset of total coverage. Recall that mean coverage for the non-penetrating scenario was 48.6%. Of this total amount of coverage, the RQ-4 is the largest contributor at 38.2% of the total, slightly ahead of the U-2 at 36.9%. These two platforms alone account for over 75% of the total coverage. This is not unexpected given the superior sensor packages carried by these airframes. It appeared in pre-simulation analysis that the RQ-1 would not be a primary contributor to total coverage given its relatively limited sensor range. This is clearly not the case. The long dwell time apparently gives the RQ-1 a significant advantage over the P-3 and the RC-135. The RC-135s total contribution is likely limited since it carries only the SIGINT sensor. This disadvantage is compounded by the fact that there are fewer SIGINT targets in the scenario than EO/IR or SAR targets. See Figure 62 for a comparison of coverage by platform type.

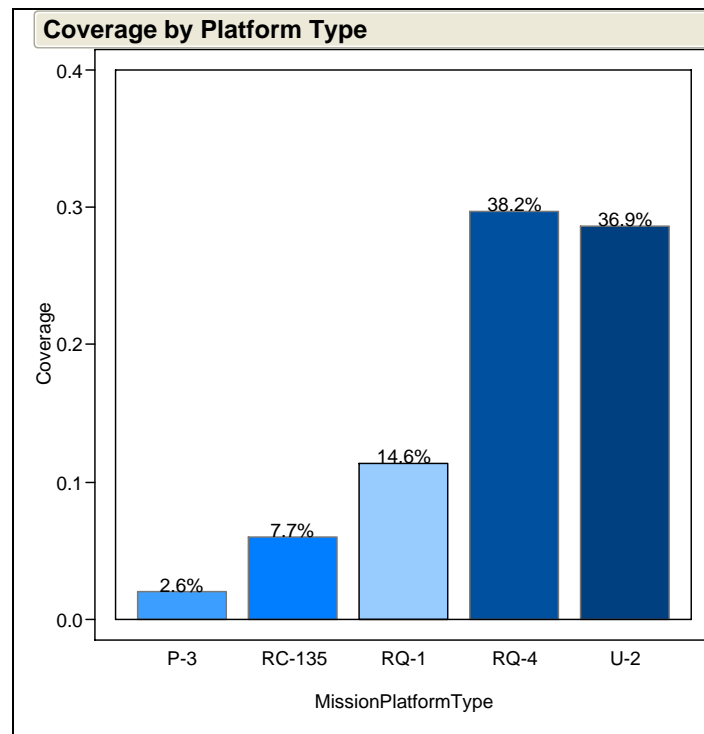


Figure 62. Coverage by Platform Type



### 3. Penetrating Scenario Coverage

#### a. Coverage Regression Model

An initial plot of the distribution and summary statistics for 274 design points in the penetrating scenario is shown in Figure 63. The coverage results appear to be roughly normally distributed with a mean of 0.48. The seven low outlying and four high outlying data points in the outlier box plot warrant examination.

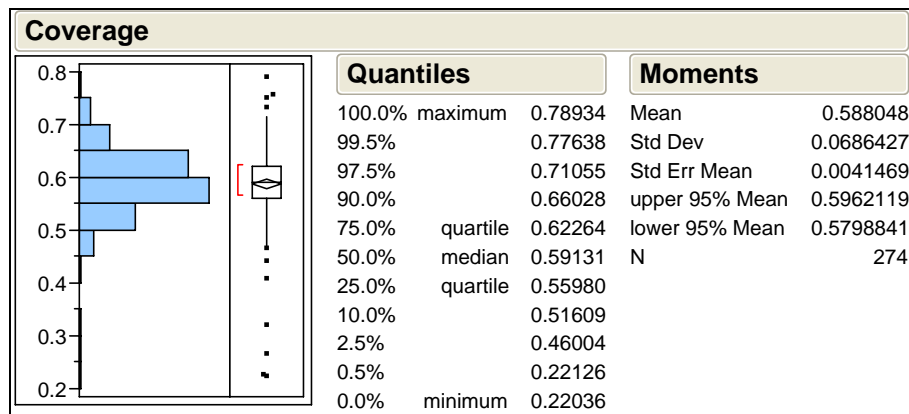


Figure 63. Penetrating Scenario: Distribution and Summary Statistics of Mission Area Coverage

An examination of the data reveals that four of the low outlying data points 1, 2, 4, and 265 are the result of design points having only a single base available for operations (See Table 14). Even though each operating location had a full compliment of aircraft (21 total airframes), the mean coverage ranked at the bottom of all the results. Having a single operating base available to ISR platforms in a region of the size encompassed in this study is unrealistic. Therefore, the design points that include only one operating location are not considered in the remained of this analysis. The remaining outliers, data points 11, 38, and 27, had ISR platforms at all locations (17, 33, and 30 total airframes, respectively, out of a possible 84). The low total numbers of aircraft, coupled with low numbers of U-2 (3, 6, and 3, respectively) and RQ-4 (2, 2, and 3, respectively) airframes appears to be the reason for the low mean coverage. There is no justification for removing these design points from the data set in further analysis.

Design Point	A RQ-4	A RQ-1	A P-3	A RC-135	A U-2	B RQ-4	B RQ-1	B P-3	B RC-135	B U-2	C RQ-4	C RQ-1	C P-3	C RC-135	C U-2	D RQ-4	D RQ-1	D P-3	D RC-135	D U-2	OPT INT	Coverage
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	6	6	3	3	3.25	0.222771
2	0	0	0	0	0	0	0	0	0	0	3	6	6	3	3	0	0	0	0	0	3.25	0.220356
4	0	0	0	0	0	3	6	6	3	3	0	0	0	0	0	0	0	0	0	0	3.25	0.318629
11	0	1	0	1	0	0	1	2	0	1	1	1	2	0	1	1	2	1	1	1	0.98	0.404777
28	0	3	2	3	2	0	5	1	1	1	0	4	0	2	2	2	1	3	0	1	3.91	0.462888
37	0	4	4	2	2	2	5	0	0	1	0	2	1	3	0	1	0	0	3	0	1.45	0.440144
265	3	6	6	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.25	0.263309

Table 14. Penetrating Scenario: Low Outlying Data Points

Four high outlier data points were also identified, 86, 261, 273 and 274 (See Table 15). Each of these points contains high numbers of U-2 and RQ-4 aircraft, in fact, high numbers of all aircraft (56, 68, 84, and 84 total aircraft, respectively out of a possible 84). These design points, while possibly unrealistic in terms of available ISR platforms, do not violate any of the assumptions of the modeling scenario and do not warrant removal from the data set.

Design Point	A RQ-4	A RQ-1	A P-3	A RC-135	A U-2	B RQ-4	B RQ-1	B P-3	B RC-135	B U-2	C RQ-4	C RQ-1	C P-3	C RC-135	C U-2	D RQ-4	D RQ-1	D P-3	D RC-135	D U-2	OPT INT	Coverage
86	1	2	6	0	3	3	4	6	2	1	3	5	5	2	3	1	2	3	1	3	5.35	0.728791
261	3	5	6	2	3	3	5	4	3	2	2	5	4	3	2	2	5	5	2	2	5.98	0.754785
273	3	6	6	3	3	3	6	6	3	3	3	6	6	3	3	3	6	6	3	3	3.25	0.749603
274	3	6	6	3	3	3	6	6	3	3	3	6	6	3	3	3	6	6	3	3	6	0.789344

Table 15. Penetrating Scenario: High Outlying Data Points

After removing the single base outliers, the distribution and summary statistics for the penetrating scenario data were recalculated (See Figure 64). The mean coverage increases by approximately 1% and the remaining data more closely approximates a normal distribution.

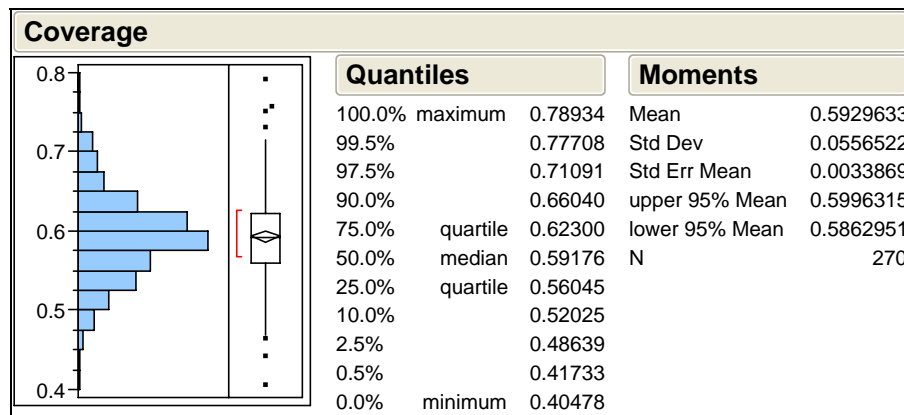


Figure 64. Penetrating Scenario: Distribution and Summary Statistics of Mission Area Coverage (single base outliers removed)

From the final 270 design point dataset a full quadratic model with main effect, interaction, and polynomial terms was created. The Stepwise Regression Control settings within JMP were as follows:

- Probability to enter: 0.01
- Probability to leave: 0.01
- Direction: Forward

The Construct Model Effects macros for Factorial to Degree and Polynomial to Degree were set at 2 to allow the possibility of two-way interaction and quadratic terms.

The resultant model achieves an R-squared of 0.71 and contains 16 main effect terms, 7 interaction terms, and 4 second order terms. See Figures 65 and 66 for the regression plot and a list of the regression model terms. Note that the optimization interval (OPT INT) is clearly the most significant factor in the model.

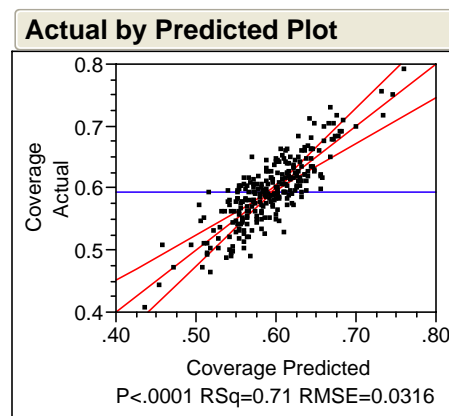


Figure 65. Actual by Predicted Coverage Plot for Full Quadratic Model

Parameter Estimates				
Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.3606258	0.011655	30.94	<.0001*
A RQ-4	0.0054156	0.001988	2.72	0.0069*
A RQ-1	0.0065338	0.001058	6.17	<.0001*
A P-3	0.0061525	0.001063	5.79	<.0001*
A U-2	0.0059377	0.001998	2.97	0.0033*
B RQ-4	0.0080442	0.00197	4.08	<.0001*
B P-3	0.003962	0.001046	3.79	0.0002*
B U-2	0.0064787	0.001974	3.28	0.0012*
C RQ-4	0.0107559	0.001982	5.43	<.0001*
C P-3	0.0022811	0.001052	2.17	0.0311*
C U-2	0.0050889	0.001977	2.57	0.0107*
D RQ-4	0.0063526	0.001993	3.19	0.0016*
D RQ-1	0.003488	0.001069	3.26	0.0013*
D P-3	0.0081541	0.001063	7.67	<.0001*
D RC-135	0.0071914	0.002009	3.58	0.0004*
D U-2	0.0136722	0.002008	6.81	<.0001*
OPT INT	0.0139716	0.001338	10.45	<.0001*
(A RQ-4-1.52963)*(OPT INT-3.46986)	-0.003346	0.001438	-2.33	0.0208*
(A RQ-1-3.05926)*(D U-2-1.52963)	0.0032962	0.001103	2.99	0.0031*
(A P-3-3.05926)*(C RQ-4-1.52963)	0.0009105	0.000949	0.96	0.3383
(A U-2-1.52963)*(D RQ-4-1.52963)	-0.004324	0.001949	-2.22	0.0274*
(B RQ-4-1.52963)*(B U-2-1.52963)	-0.003686	0.002221	-1.66	0.0983
(C RQ-4-1.52963)*(OPT INT-3.46986)	-0.003959	0.001359	-2.91	0.0039*
(C P-3-3.05926)*(C U-2-1.52963)	-0.001152	0.001217	-0.95	0.3448
(D RQ-1-3.05926)*(D RC-135-1.52963)	-0.003878	0.001108	-3.50	0.0005*
(D P-3-3.05926)*(OPT INT-3.46986)	0.0006726	0.000747	0.90	0.3688
(B P-3-3.05926)*(B P-3-3.05926)	-0.001511	0.000673	-2.25	0.0256*
(D U-2-1.52963)*(D U-2-1.52963)	-0.008468	0.00225	-3.76	0.0002*

Figure 66. Full Quadratic Coverage Model Terms

The full quadratic model for the penetrating scenario differs significantly from the non-penetrating scenario model in the number of terms included. In the penetrating model all of the platform types show up at least once, where as in the non-penetrating model, P-3 were not represented at all. The main similarity between the non-penetrating model and the penetrating model is that the U-2 and RQ-4 are represented at every base as significant dependent variables in the regression equation.

To test the validity of the Coverage Full Quadratic Regression model the regression assumptions from Part A of this chapter must be verified. The Actual by Predicted Plot in Figure 65 indicates that the relationship between the response variable (coverage) and the regressors is nearly linear. The apparently random cloud of data points with a mean of zero in the Residual by Predicted Plot, Figure 67, confirms that the

requirements for a zero mean, constant variance, and lack of correlation of the residuals is met. Compliance with the normality assumption is shown in Figure 68 by a histogram of the residuals overlaid with a normal curve and a normal quantile plot.

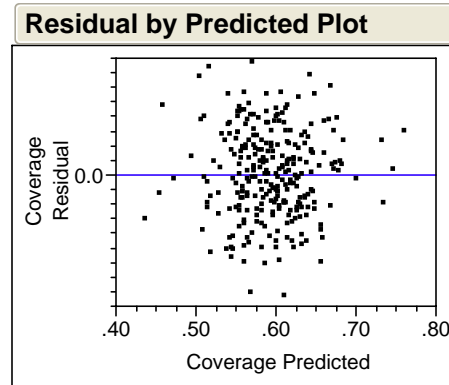


Figure 67. Residual by Predicted Plot for Coverage Model

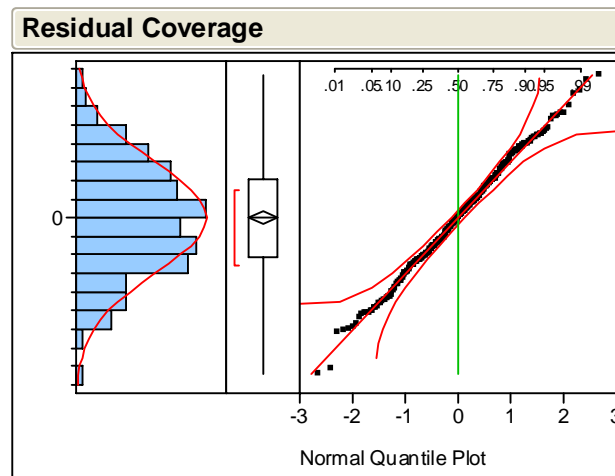


Figure 68. Histogram and Normal Quantile Plot of Residuals for the Coverage Model

### ***b. Coverage Factor Interactions***

The Interaction Profile matrix for the coverage model is 16 x 16 cells, too large to meaningfully display in this context. The matrix contains 18 cells with significant interactions, however, just as in the non-penetrating scenario, the minimum and maximum factor setting levels result in only marginal changes to overall coverage. Given the minimal effect of the interactions, additional detailed discussion of the individual interactions is unwarranted for this study.

*c. Coverage Regression Tree Analysis*

Just as with the non-penetrating scenario, to determine the number of splits that would continue to yield additional explanatory value for Coverage, 20 splits were done in rapid succession to record the R-squared value without regard to the content or structure of the regression tree. These R-squared values were plotted to find the point that the curve began to plateau, indicating diminishing returns from each successive split. In this case, 10 splits are warranted. Figure 69 provides a plot of the R-squared values against the number of splits.

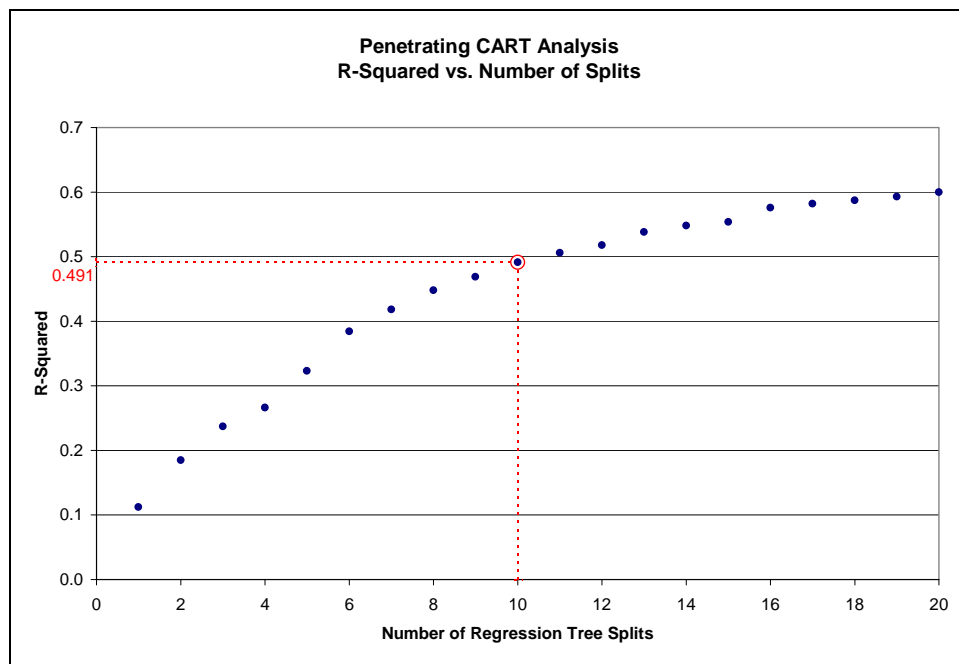


Figure 69. R-Squared vs. Number of Regression Tree Splits

Figure 70 shows the regression tree for Coverage with 10 splits. The full tree and partition graph can be found in Appendix J. The first split indicates that better coverage is obtained when the optimization interval is 2.1 hours or greater. In the second split, coverage is improved by having one or more U-2s at Base D. The third partition demonstrates improved coverage when there are three, the maximum number of RQ-4s, at Base C. The fourth split indicates that better coverage is gained by having at least one RQ-4 at Base D. The fifth split indicates that better coverage is obtained with the maximum number (six) P-3s at Base A. The sixth split indicates that coverage is

improved by the stationing at least five RQ-1s at Base C. The seventh split is a return to the optimization interval, showing that coverage improves with optimization intervals of 5.37 hours or more. Note that six hours is the maximum optimization interval for this study. The eighth split is on having two or more RQ-1s at Base D. Split nine indicates improved coverage by stationing two or more RC-135s at Base D. The final split is on RQ-1s at Base A, this time indicating improved coverage with six platforms, the maximum number.

As in the penetrating scenario, optimization interval appears twice and is the most significant factor. Interestingly, the optimization interval is the most significant factor in both the penetrating and non-penetrating scenarios; however, its level has the opposite effect on coverage. In the non-penetrating scenario, as the optimization interval increases, coverage goes down. The opposite occurs in the penetrating scenario, where coverage improves as the optimization interval goes up. This disparate behavior is likely due to addition of mission areas, and consequently, more reachable missions in the penetrating scenario. A greater variety of mission area to mission assignment options reduces the chance of the most capable platforms going unused due to assignment saturation caused by shorter optimization intervals.

In this regression tree, all types of aircraft are represented; however, Base B does not appear. That is not to suggest that Base B is irrelevant, only that it is not a contributor to the most significant factors. Recall that Base B is furthest from the COI. The presence of all platform types is in contrast to the non-penetrating scenario where U-2s were heavily represented and P-3s not at all.

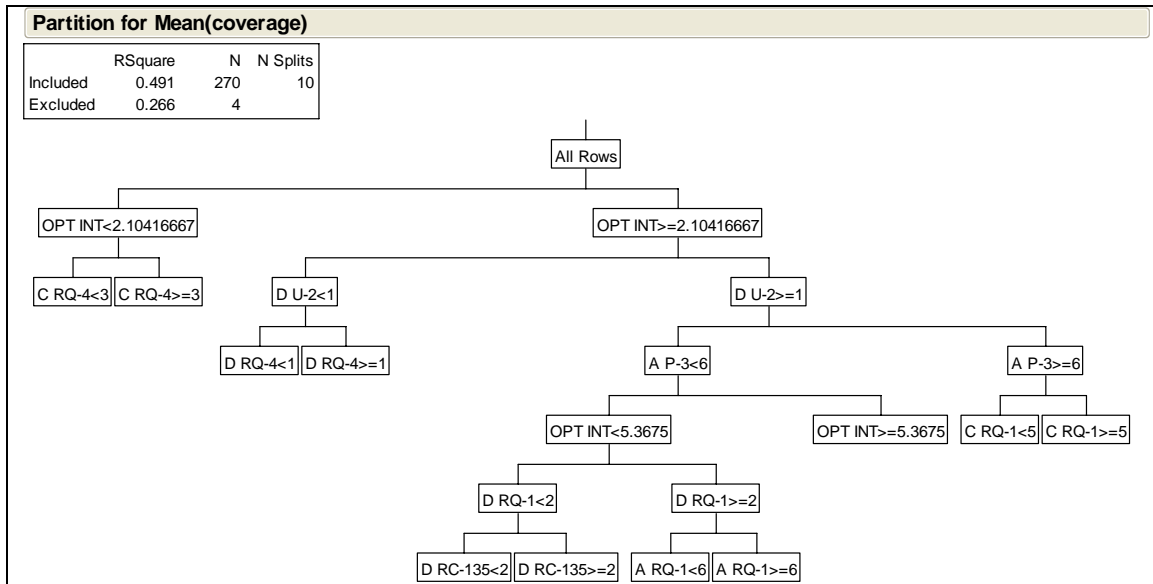


Figure 70. Regression Tree for Coverage

#### d. Coverage Contour Plot Analysis

To explore the relationship between the various types of ISR platforms and the total number of platforms, contour plots were generated. The various color filled regions of the plot represent the amount of coverage attained as the number of each platform and total aircraft vary. Recall from the non-penetrating scenario contour plot analysis that the combinatorial nature of the problem and strong interactions of the regressors result in a non-smooth contour plot. Also, note that the surface is affected by changes in other factors; therefore, trends in the contour plots are more important than specific values.

Figure 71 shows that in order achieve the best coverage, approximately 60 total aircraft are required with at least 4 U-2s. Once 60 total aircraft are available, the addition of more U-2 platforms continues to improve coverage.



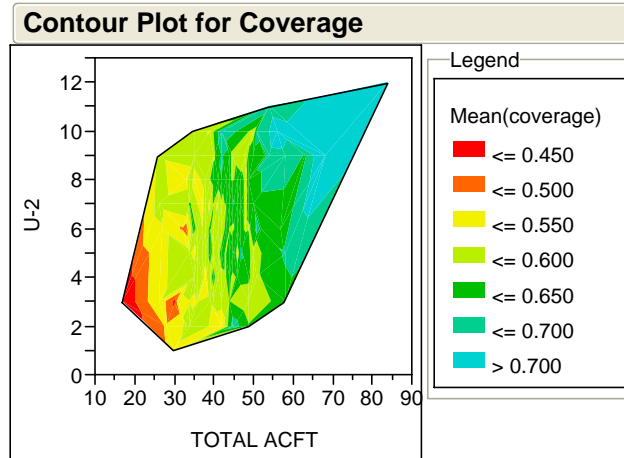


Figure 71. Coverage Contour Plot for U-2 vs. Total Aircraft

The relationship between the number of RQ-4s and total aircraft is illustrated in Figure 72. The total number of aircraft necessary to achieve the best levels of coverage is lower than for the U-2 once there are four or more RQ-4s in the simulation. As with the U-2, coverage continues to improve with the addition of more RQ-4 airframes.

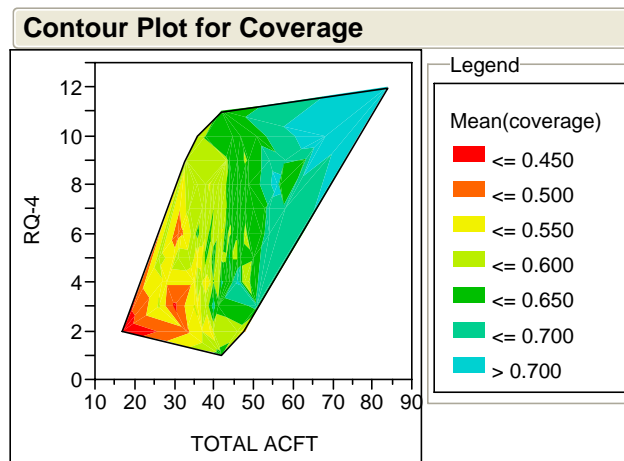


Figure 72. Coverage Contour Plot for RQ-4 vs. Total Aircraft

Figure 73 demonstrates the value of the RC-135 in relation to total aircraft. The maximum levels of coverage appear to be achieved when there are at least 55 total aircraft and 3 or more RC-135s. The RC-135 continues to maximize coverage as its quantity and the total number of aircraft rise.

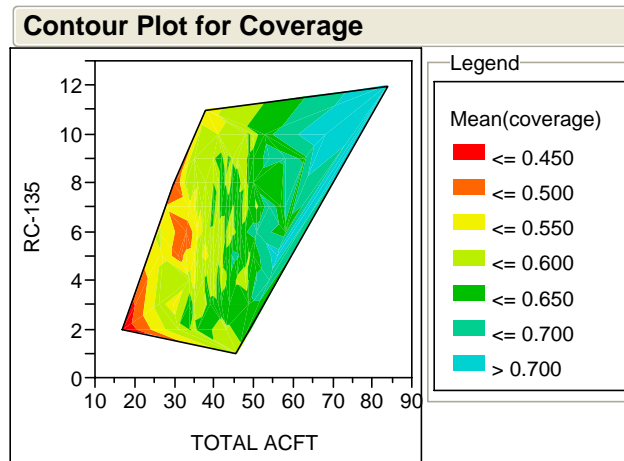


Figure 73. Coverage Contour Plot for RC-135 vs. Total Aircraft

Figure 74 displays the relationship between the quantity of P-3 airframes and the total number of aircraft. The best levels of coverage are reached when there are more than 10 P-3s and 60 or more total aircraft. Beyond these levels, coverage continues to improve.

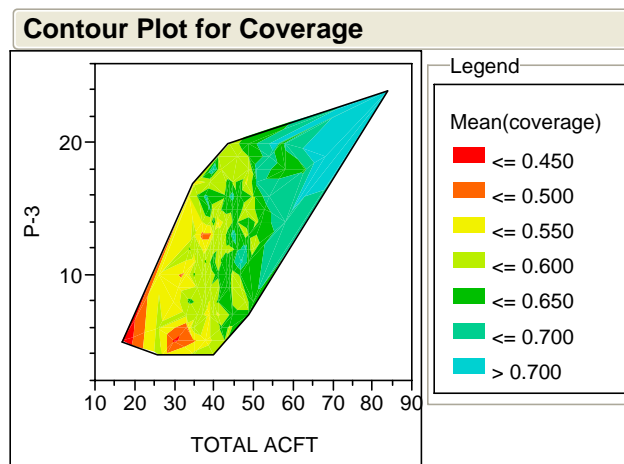


Figure 74. Coverage Contour Plot for P-3 vs. Total Aircraft

Figure 75 shows that the best coverage is attained with approximately 60 total aircraft and more than 12 RQ-1s. As with all of the other platform types, coverage continues to rise with the addition of more airframes.

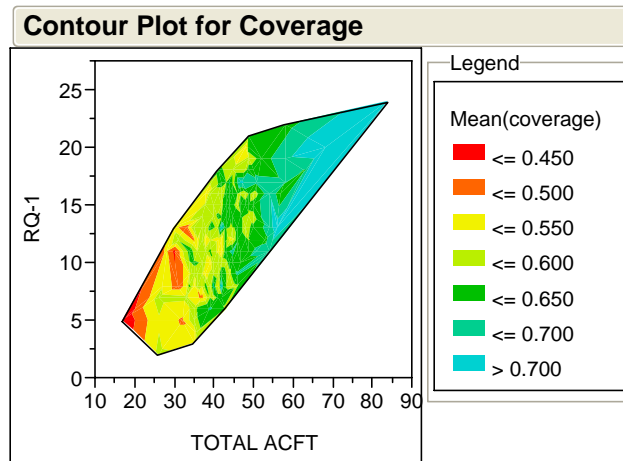


Figure 75. Coverage Contour Plot for RQ-1 vs. Total Aircraft

#### 4. Coverage by Type

The Coverage by Type MOE is a subset of total coverage. Figure 76 displays the amount of coverage by each platform type. Recall that mean coverage for the non-penetrating scenario was 59.2%. Of this total amount of coverage the RQ-4 is the largest contributor at 52.3% of the total, far exceeding the next closest contributor, the U-2 at 19.5%. In the penetrating scenario, these two platforms account for nearly 72% of the total coverage. Again, this is not unexpected given the superior sensor packages carried by these airframes. The ability of the RQ-4 to remain on station, along with its highly capable sensor package, clearly demonstrates its value. The ability to use mission areas in country appears to have boosted the P-3s contribution in the penetrating scenario. The utility of the RQ-1 declines slightly in the penetrating scenario, likely due to the enhanced collection ability of the other platforms given the addition of the penetrating mission areas. The RC-135s total contribution appears severely limited by its single sensor capability. Also, as in the non-penetrating scenario, this disadvantage is compounded by the fact that there are fewer SIGINT targets in the scenario than EO/IR or SAR targets.

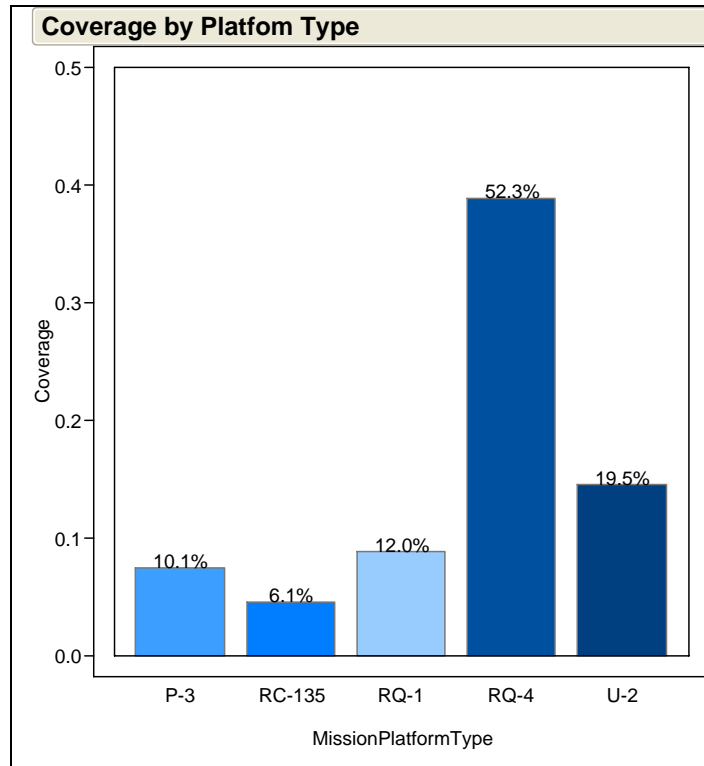


Figure 76. Coverage by Platform Type

## 5. Attrition

Attrition is a relatively uninteresting MOE for this analysis. The lack of realistic unclassified performance data and parameters for the threat platforms and vulnerability data for the ISR platforms resulted in a generic treatment of this data within the simulation. The  $P_k$  for all ISR platforms at the minimum and maximum surface-to-air missile range was set at 0.6 and 0.5, respectively. Consequently, the ISR platforms were attrited in exact proportion to their presence in the scenario (See Figure 77). Of note, 4,139,948 aircraft sorties were generated and flown in this simulation, 2% or 94,390 were killed. Attrition for studies conducted in a classified environment with real world parameters would likely differ significantly from the results found in this experiment.

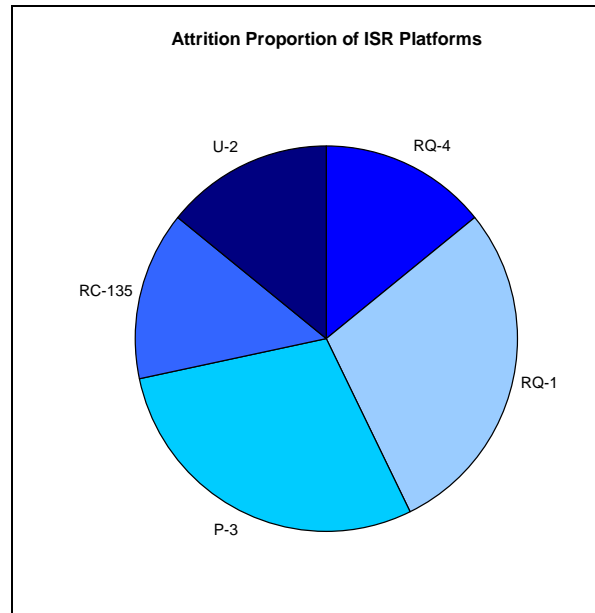


Figure 77. Proportional Attrition of ISR Platforms

## 6. Comparison of Non-Penetrating vs. Penetrating Results

Several significant similarities and differences between the output from the non-penetrating and penetrating scenarios were identified. These findings and an explanation of the underlying factors is provided.

### *a. Coverage*

As expected, the coverage for the penetrating scenario exceeds that of the non-penetrating scenario (See Figure 78). The non-penetrating scenario resulted in a mean coverage of 0.49, with a standard deviation of 0.02, and maximum and minimum values of 0.53 and 0.43, respectively. The penetrating scenario yielded a mean coverage of 0.59, with a standard deviation of 0.06, and maximum and minimum values of 0.79 and 0.40, respectively. The reduced coverage in the non-penetrating scenario is due to the physical inability of the sensors to range the targets. It must be noted that coverage for the penetrating scenario could potentially be much lower if the attrition rate was increased.

While the penetrating scenario provides 10% more mean coverage, its results contain 3 times the variability. In fact, the lowest coverage value is actually found

in the results of the penetrating scenario. This variability is due to both the stochastic nature of the penetrating scenario and relative increased complexity of the approximate dynamic programming approach due to the addition of more mission areas.

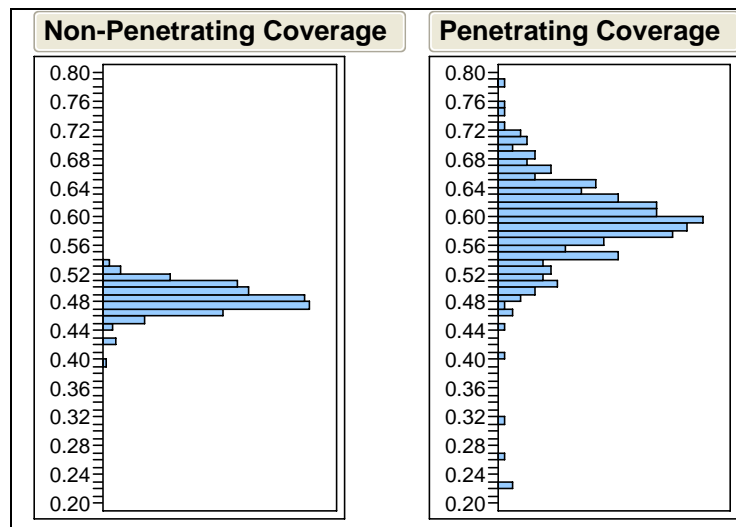


Figure 78. Penetrating vs. Non-Penetrating Coverage

### c. Coverage by Type

A comparison of the coverage by platform type for each scenario is shown in Figure 79. The RQ-4 provides the greatest amount of coverage in both scenarios; however it is nearly matched by the U-2 in the non-penetrating scenario. This disparity is likely due to the RQ-4s ability to remain on-station, particularly in the penetrating scenario where additional transit time is required to reach the mission areas. The RQ-4 and U-2 superior coverage is not unexpected as both airframes carry all three of the sensor types considered for this study. The substantial demand for the three sensor types impacts the value of the most capable platforms. The combined coverage of the remaining platforms, the RQ-1, the P-3, and the RC-135, is approximately 25% of the total in both scenarios. None of these aircraft has more than two sensor types, lowering their ability to contribute significantly to coverage. Of note, the P-3 provides almost no value in the non-penetrating scenario, likely due to its relatively short on station time when compared to the RQ-1 which has a similar sensor package.

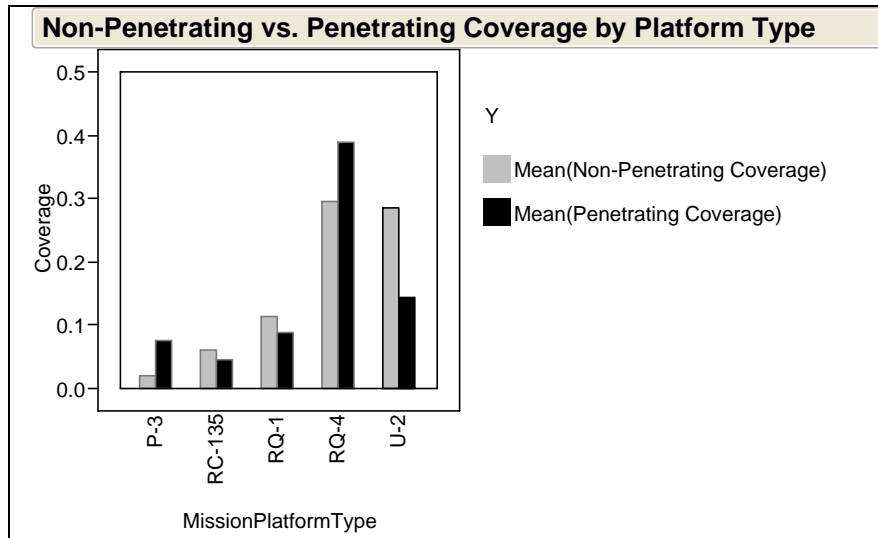


Figure 79. Non-Penetrating vs. Penetrating Coverage by Platform Type

***b. Factor Comparison***

Figure 80 illustrates the opposite effect demonstrated by the optimization interval factor with respect to coverage. In the non-penetrating scenario, shorter optimization intervals are better, but in the penetrating scenario longer optimization intervals yield improved coverage. This disparity is explained by the increase in mission areas and reachable missions available in the penetrating scenario. With more mission areas and missions included in each optimization, there is less chance that the more capable airframes will be underutilized due to assignment saturation. Recall from Chapter II that all open missions and available airframes are matched at each optimization event. When there are a greater number of mission areas and missions available, as in the penetrating scenario, there is less chance that the better platforms will be assigned to low target density areas or not used at all.

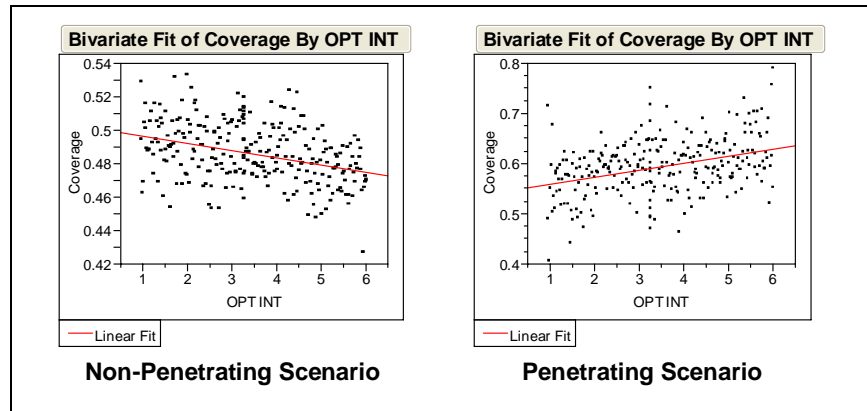


Figure 80. Bivariate Fit of Coverage by Optimization Interval for the Non-Penetrating and Penetrating Scenarios

The U-2 and the RQ-4 show up as significant factors in both scenarios. An examination of the regression trees from each scenario, Figures 60 (page 90) and 70 (page 99), reveals that the dataset is partitioned on U-2 as a factor before the RQ-4 even though the RQ-4 provides a greater percentage of the overall coverage in both scenario. This is due to the RQ-4s long endurance. The long dwell time of the RQ-4 means that it is involved in fewer optimization events and therefore does not contribute to the variability of the coverage in the same way as the U-2.



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## **VI. FINDINGS AND RECOMMENDATIONS**

### **A. SIGNIFICANT FINDINGS**

JDAFS was exercised to determine its viability for use in future studies. In doing so, scenarios were constructed and simulations run based on Nearly Orthogonal Latin Hypercube design of experiment methodology. Based on these experiments, data analysis was conducted on the resultant simulation output and issues with the JDAFS model were identified for enhancement or correction. The significant findings from this research are summarized below.

#### **1. Data Analysis Issues**

- Optimization is the most significant factor in both the scenarios, but has the opposite effect. In the non-penetrating scenario, shorter optimization intervals are better, but in the penetrating scenario longer optimization intervals yield improved coverage. Increased assignment options in the penetrating scenario causes this disparate behavior by the optimization interval factor.
- The U-2 is the most important platform factor in explaining the variability in both scenarios.
- The RQ-4 results in the majority of mission coverage for both scenarios due to its ability to remain on station.
- Coverage is not necessarily improved by adding more ISR assets in the non-penetrating scenario.
- Coverage is improved by the addition of assets in the penetrating scenario. Coverage would likely eventually also plateau with diminishing returns from the addition of more aircraft in this scenario. The maximum number of airframes in the scenario was not sufficient to explore this behavior.
- Penetrating ISR platforms average 20% more mean coverage than non-penetrating platforms.

#### **2. Issues Identified and Corrected During Preliminary Testing**

The exercise of the JDAFS model prior to the commencement of production runs identified a number of bugs and deficiencies. These discrepancies were all promptly addressed and corrected by the model developers. The following is a summary of the issues and modifications made to JDAFS.

***a. JDAFS Architectural Issues***

Initial attempts to run JDAFS in a cluster environment were unsuccessful. JDAFS was originally written to be run from a GUI. The basic window object for a GUI in the Java programming language is called a "JFrame". The model initialization code for JDAFS was placed inside a JFrame constructor. Thus, even if no window was opened, a JFrame needed to be constructed to run JDAFS. In order to construct a JFrame, Java polls the environment to determine all of the characteristics of the GUI environment. Since there wasn't any such environment when running JDAFS from the command line in a cluster environment, this caused a "Null pointer exception", i.e., a reference to something which doesn't exist. This is a terminal error for a Java program. The model developers removed the model initialization code from JDAFS and built a completely new installer that ensured cluster compatibility.

Aircraft routing was initially done on a straight line path from a base to its associated mission areas. To prevent the overflight of denied areas, it was necessary to implement a waypoint routing capability. The "route" table was added to give the ability to specify ingress and egress routes between bases and mission areas or between two mission areas.

***b. JDAFS Bugs Identified and Corrected***

JDAFS uses the Bugzilla open-source defect tracking system to allow users to report issues discovered when using the simulation. Bugzilla also provides a means for the JDAFS developers to communicate the status of correcting any deficiencies. All of the bugs identified in this research were promptly addressed and corrected, often in less than 24 hours. Table 16 list the bugs identified, their symptoms, and the necessary corrections made in JDAFS.

Symptom	Problem	Correction
JDAFS simulation failed to run to completion. An <i>Illegal State Transition Exception</i> error was thrown in JAVA.	If a mission platform was killed on the ground, its pending events were not cancelled. Since a dead platform is unable to execute its mission, JAVA throws the Illegal State Transition Exception and the simulation cannot continue.	The JDAFS JAVA code was amended to ensure all pending events are cancelled for killed mission platforms.
JDAFS Simulation optimization event took successively longer to complete, eventually resulting in a failure to run to completion.	JDAFS was not calling deleteLp() following optimization events. This resulted in a memory leak in Ipsolve. As the simulation progressed, there were insufficient memory resources for the program to continue.	A call to deleteLp() was added in the 3D CVO process in JAVA to ensure that memory resources were freed prior to each optimization event.
Unusually high coverage values were reported following simulation runs.	Platforms were receiving credit for coverage of targets that were out of range or for which LOS did not exist.	JDAFS coverage reports were corrected to ensure coverage credit was only received when platforms actually covered a mission.

Table 16. JDAFS Bugs Identified and Corrected

## B. RECOMMENDATIONS FOR FURTHER JDAFS IMPROVEMENT

JDAFS is a powerful research tool; however, a number of modifications are warranted that will improve the usability, functionality, and credibility of the model for future studies. The following changes and improvements are recommended:

- Allow ISR platforms to receive credit for collection on targets within sensor range during ingress and egress to mission areas.
- Create probability distributions to represent current and future force sensors from certified data to accurately represent the acquisition of targets by sensors in the model.
- Implement revisit valuation schemes for missions to more credibly represent ISR mission characteristics.

- Addition of joint assets (platforms, sensors, munitions, etc.) in the JDAFS database for reuse in joint studies.
- Further develop the functionality of JDAFS to more credibly represent Joint Sensors to include satellite assets.
- Provide a more robust representation of unmanned aerial vehicles with weapons and sensors that allow force-on-force analysis of differing platform mixes.
- Develop an integrated design of experiments interface that enables a quick determination of alternatives.
- Incorporate the InputGenerator and OutputGenerator scripts into the JDAFS program. The integration of these tools will eliminate the need for the pre and post-processing of data and eliminate the need to transfer excessively large files.
- Develop a simple, well documented JDAFS interface to allow an analyst to easily enter the data for the various input factors.
- Develop a comprehensive JDAFS Users/Analyst Manual.

### **C. RECOMMENDATIONS FOR FUTURE JDAFS STUDIES**

The research conducted for this thesis exercised the JDAFS model and demonstrated its utility as a simulation and data farming tool. The following areas should be considered for additional research using JDAFS:

- Exercise data farming concepts as additional development is done to the JDAFS model.
- Explore the use of JDAFS to study UAV acquisition of moving or pop-up targets.
- Conduct analysis using real world terrain and order of battle to explore multiple operational factors.
- Explore the use of JDAFS as an acquisition and capabilities requirements tool.
- Use JDAFS to explore the trade-offs associated with manned vs. unmanned ISR platforms.
- Evaluate the utility of JDAFS as a screening tool for high resolution modeling and simulation.
- Allow cueing and flexible time windows to further enhance scenario realism.

## APPENDIX A. NON-PENETRATING SCENARIO BASE TO MISSION AREA DISTANCE TABLE

		BASE			
MISSION AREA		A	B	C	D
	1	328000	1195861	1250502	1620154
	2	356629	1061925	1110502	1480154
	3	424834	939140	980502	1350154
	4	569745	936862	861140	1205242
	5	714656	956785	750824	1060331
	6	859568	997578	654149	915420
	7	1004479	1056827	578000	770509
	8	1149390	1199525	654149	625629
	9	1294301	1342698	750824	480767
	10	1439212	1486207	861140	335948
	11	1584124	1629964	980502	191269
	12	1714124	1759964	1092742	187840
	13	1854124	1899964	1217573	267739
	24	356629	1331046	1390502	1760154
MIN		328000	936862	578000	187840
MAX		1854124	1899964	1390502	1760154
MEAN		974987	1271025	938075	875094
MEDIAN		932023	1197693	920821	842965

Non-Penetrating Scenario: Base to Mission Area Distance ( in meters) Table (*The additional transit required due to waypoint routing to prevent COI overflight is included in the distance calculations for this table*).

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## APPENDIX B. PENETRATING SCENARIO BASE TO MISSION AREA DISTANCE TABLE

MISSION AREA	BASE			
	A	B	C	D
1	328000	1195861	1217573	1238258
2	356629	1061925	1092742	1223472
3	424834	939140	980502	1224003
4	566667	936862	861140	1099573
5	709744	956785	750824	980784
6	853441	997578	654149	869949
7	997489	1056827	578000	770509
8	1082618	1199525	654149	625629
9	1179465	1342698	750824	480767
10	1285384	1486207	861140	335948
11	1398315	1629964	980502	191269
12	1379124	1703668	1092742	187840
13	1372000	1790219	1217573	267739
24	356629	1331046	1345394	1268418
51	450000	1234909	1170470	1118034
52	672301	1504024	1329018	1000744
53	672301	1134411	912956	912079
54	700000	1346291	1110180	873212
55	939415	1767767	1500000	921954
56	863134	1553222	1250000	782624
57	863134	1312440	950000	701783
58	939415	1133578	700000	728011
59	1000000	1523975	1110180	585235
60	1082953	1727104	1329018	638661
61	1082953	1416929	912956	488148
62	1250000	1698529	1170470	360555
<b>MIN</b>	328000	936862	578000	187840
<b>MAX</b>	1398315	1790219	1500000	1268418
<b>MEAN</b>	877152	1345442	1018558	764431
<b>MEDIAN</b>	901274	1336872	1036622	776566

Penetrating Scenario: Base to Mission Area Distance (in meters) Table



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## APPENDIX C. BASE ‘A’ TRANSIT AND ON-STATION STATISTICS

NON-PENETRATING SCENARIO										
MISSION AREA	A									
	RQ-4		RQ-1		P-3		RC-135		U-2	
	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA
1	1.041799	34.9582	4.427646	19.57235	1.55356	10.44644	0.814271	10.18573	0.795981	9.204019
2	1.13273	34.86727	4.814102	19.1859	1.689159	10.31084	0.885342	10.11466	0.865456	9.134544
3	1.349365	34.65063	5.734801	18.2652	2.012211	9.987789	1.054664	9.945336	1.030976	8.969024
4	1.809634	34.19037	7.690946	16.30905	2.698577	9.301423	1.414411	9.585589	1.382642	8.617358
5	2.269904	33.7301	9.64709	14.35291	3.384944	8.615056	1.774158	9.225842	1.734308	8.265692
6	2.730173	33.26983	11.60323	12.39677	4.07131	7.92869	2.133904	8.866096	2.085975	7.914025
7	3.190442	32.80956	13.55938	10.44062	4.757677	7.242323	2.493651	8.506349	2.437641	7.562359
8	3.650711	32.34929	15.51552	8.484476	5.444043	6.555957	2.853398	8.146602	2.789308	7.210692
9	4.110981	31.88902	17.47167	6.528332	6.13041	5.86959	3.213144	7.786856	3.140974	6.859026
10	4.57125	31.42875	19.42781	4.572188	6.816776	5.183224	3.572891	7.427109	3.49264	6.50736
11	5.031519	30.96848	21.38396	2.616043	7.503143	4.496857	3.932638	7.067362	3.844307	6.155693
12	5.444427	30.55557	23.13882	0.861184	8.118883	3.881117	4.255367	6.744633	4.159787	5.840213
13	5.889098	30.1109	24	0	8.781988	3.218012	4.602922	6.397078	4.499535	5.500465
24	1.13273	34.86727	4.814102	19.1859	1.689159	10.31084	0.885342	10.11466	0.865456	9.134544
MIN	1.04	30.11	4.43	0.00	1.55	3.22	0.81	6.40	0.80	5.50
MAX	5.89	34.96	25.03	19.57	8.78	10.45	4.60	10.19	4.50	9.20
MEAN	3.10	32.90	13.16	10.84	4.62	7.38	2.42	8.58	2.37	7.63
MEDIAN	2.96	33.04	12.58	11.42	4.41	7.59	2.31	8.69	2.26	7.74

PENETRATING SCENARIO										
MISSION AREA	A									
	RQ-4		RQ-1		P-3		RC-135		U-2	
	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA
1	1.041799	34.9582	4.427646	19.57235	1.55356	10.44644	0.814271	10.18573	0.795981	9.204019
2	1.13273	34.86727	4.814102	19.1859	1.689159	10.31084	0.885342	10.11466	0.865456	9.134544
3	1.349365	34.65063	5.734801	18.2652	2.012211	9.987789	1.054664	9.945336	1.030976	8.969024
4	1.799856	34.20014	7.64939	16.35061	2.683996	9.316004	1.406769	9.593231	1.375171	8.624829
5	2.254302	33.7457	9.580782	14.41922	3.361678	8.638322	1.761963	9.238037	1.722388	8.277612
6	2.710713	33.28929	11.52053	12.47947	4.042291	7.957709	2.118694	8.881306	2.071106	7.928894
7	3.168241	32.83176	13.46502	10.53498	4.724569	7.275431	2.476298	8.523702	2.420678	7.579322
8	3.438628	32.56137	14.61417	9.385829	5.127779	6.872221	2.687634	8.312366	2.627267	7.372733
9	3.746235	32.25376	15.9215	8.0785	5.586491	6.413509	2.928059	8.071941	2.862292	7.137708
10	4.082657	31.91734	17.35129	6.648708	6.088173	5.911827	3.191007	7.808993	3.119333	6.880667
11	4.44135	31.55865	18.87574	5.124262	6.623066	5.376934	3.471361	7.528639	3.393391	6.606609
12	4.380398	31.6196	18.61669	5.38331	6.532172	5.467828	3.423721	7.576279	3.346821	6.653179
13	4.357769	31.64223	18.52052	5.479482	6.498427	5.501573	3.406034	7.593966	3.329531	6.670469
24	1.13273	34.86727	4.814102	19.1859	1.689159	10.31084	0.885342	10.11466	0.865456	9.134544
51	1.429297	34.5707	6.074514	17.92549	2.131408	9.868592	1.11714	9.88286	1.092047	8.907953
52	2.135372	33.86463	9.075331	14.92467	3.184327	8.815673	1.669008	9.330992	1.63152	8.36848
53	2.135372	33.86463	9.075331	14.92467	3.184327	8.815673	1.669008	9.330992	1.63152	8.36848
54	2.223352	33.77665	9.449244	14.55076	3.315524	8.684476	1.737773	9.262227	1.698741	8.301259
55	2.983784	33.01622	12.68108	11.31892	4.449503	7.550497	2.332127	8.667873	2.279745	7.720255
56	2.7415	33.2585	11.65137	12.34863	4.088202	7.911798	2.142758	8.857242	2.094629	7.905371
57	2.7415	33.2585	11.65137	12.34863	4.088202	7.911798	2.142758	8.857242	2.094629	7.905371
58	2.983784	33.01622	12.68108	11.31892	4.449503	7.550497	2.332127	8.667873	2.279745	7.720255
59	3.176216	32.82378	13.49892	10.50108	4.736463	7.263537	2.482532	8.517468	2.426772	7.573228
60	3.439694	32.56031	14.6187	9.381299	5.129369	6.870631	2.688467	8.311533	2.628081	7.371919
61	3.439694	32.56031	14.6187	9.381299	5.129369	6.870631	2.688467	8.311533	2.628081	7.371919
62	3.970271	32.02973	16.87365	7.12635	5.920579	6.079421	3.103165	7.896835	3.033465	6.966535
MIN	1.04	31.56	4.43	5.12	1.55	5.38	0.81	7.53	0.80	6.61
MAX	4.44	34.96	18.88	19.57	6.62	10.45	3.47	10.19	3.39	9.20
MEAN	2.79	33.21	11.84	12.16	4.15	7.85	2.18	8.82	2.13	7.87
MEDIAN	2.86	33.14	12.17	11.83	4.27	7.73	2.24	8.76	2.19	7.81

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## APPENDIX D. BASE ‘B’ TRANSIT AND ON-STATION STATISTICS

NON-PENETRATING SCENARIO										
MISSION AREA	B									
	RQ-4		RQ-1		P-3		RC-135		U-2	
	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA
1	3.798314	32.20169	16.14283	7.857165	5.664153	6.335847	2.968764	8.031236	2.902083	7.097917
2	3.372903	32.6271	14.33484	9.665164	5.029767	6.970233	2.636262	8.363738	2.577049	7.422951
3	2.982912	33.01709	12.67738	11.32262	4.448202	7.551798	2.331445	8.668555	2.279079	7.720921
4	2.975678	33.02432	12.64663	11.35337	4.437415	7.562585	2.325791	8.674209	2.273552	7.726448
5	3.038955	32.96104	12.91556	11.08444	4.531776	7.468224	2.375249	8.624751	2.321899	7.678101
6	3.168523	32.83148	13.46622	10.53378	4.72499	7.27501	2.476519	8.523481	2.420894	7.579106
7	3.356712	32.64329	14.26603	9.733972	5.005624	6.994376	2.623608	8.376392	2.564679	7.435321
8	3.809952	32.19005	16.1923	7.807702	5.681508	6.318492	2.977861	8.022139	2.910975	7.089025
9	4.264698	31.7353	18.12497	5.875032	6.359638	5.640362	3.33329	7.66671	3.258421	6.741579
10	4.720515	31.27948	20.06219	3.93781	7.039365	4.960635	3.689557	7.310443	3.606686	6.393314
11	5.17712	30.82288	22.00276	1.997241	7.720266	4.279734	4.046439	6.953561	3.955552	6.044448
12	5.590028	30.40997	23.75762	0.242381	8.336007	3.663993	4.369168	6.630832	4.271033	5.728967
13	6.034698	29.9653	24	0	8.999112	3.000888	4.716723	6.283277	4.610781	5.389219
24	4.227691	31.77231	17.96769	6.032314	6.304451	5.695549	3.304365	7.695635	3.230146	6.769854
MIN	2.98	29.97	12.65	0.00	4.44	3.00	2.33	6.28	2.27	5.39
MAX	6.03	33.02	25.65	11.35	9.00	7.56	4.72	8.67	4.61	7.73
MEAN	4.04	31.96	17.16	6.84	6.02	5.98	3.16	7.84	3.08	6.92
MEDIAN	3.80	32.20	16.17	7.83	5.67	6.33	2.97	8.03	2.91	7.09

PENETRATING SCENARIO										
MISSION AREA	B									
	RQ-4		RQ-1		P-3		RC-135		U-2	
	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA
1	3.798314	32.20169	16.14283	7.857165	5.664153	6.335847	2.968764	8.031236	2.902083	7.097917
2	3.372903	32.6271	14.33484	9.665164	5.029767	6.970233	2.636262	8.363738	2.577049	7.422951
3	2.982912	33.01709	12.67738	11.32262	4.448202	7.551798	2.331445	8.668555	2.279079	7.720921
4	2.975678	33.02432	12.64663	11.35337	4.437415	7.562585	2.325791	8.674209	2.273552	7.726448
5	3.038955	32.96104	12.91556	11.08444	4.531776	7.468224	2.375249	8.624751	2.321899	7.678101
6	3.168523	32.83148	13.46622	10.53378	4.72499	7.27501	2.476519	8.523481	2.420894	7.579106
7	3.356712	32.64329	14.26603	9.733972	5.005624	6.994376	2.623608	8.376392	2.564679	7.435321
8	3.809952	32.19005	16.1923	7.807702	5.681508	6.318492	2.977861	8.022139	2.910975	7.089025
9	4.264698	31.7353	18.12497	5.875032	6.359638	5.640362	3.33329	7.66671	3.258421	6.741579
10	4.720515	31.27948	20.06219	3.93781	7.039365	4.960635	3.689557	7.310443	3.606686	6.393314
11	5.17712	30.82288	22.00276	1.997241	7.720266	4.279734	4.046439	6.953561	3.955552	6.044448
12	5.411218	30.58878	22.99768	1.002324	8.06936	3.93064	4.22941	6.77059	4.134414	5.865586
13	5.686123	30.31388	24	0	8.479306	3.520694	4.444276	6.555724	4.344454	5.655546
24	4.227691	31.77231	17.96769	6.032314	6.304451	5.695549	3.304365	7.695635	3.230146	6.769854
51	3.922338	32.07766	16.66994	7.330063	5.849101	6.150899	3.065701	7.934299	2.996843	7.003157
52	4.777106	31.22289	20.3027	3.697301	7.123754	4.876246	3.733788	7.266212	3.649923	6.350077
53	3.603134	32.39687	15.31332	8.686678	5.373095	6.626905	2.816212	8.183788	2.752957	7.247043
54	4.276112	31.72389	18.17348	5.826523	6.376659	5.623341	3.342211	7.657789	3.267142	6.732858
55	5.614811	30.38519	23.86294	0.137055	8.372963	3.627037	4.388539	6.611461	4.289968	5.710032
56	4.933371	31.06663	20.96683	3.033174	7.356781	4.643219	3.855925	7.144075	3.769317	6.230683
57	4.168595	31.8314	17.71653	6.283471	6.216326	5.783674	3.258176	7.741824	3.184994	6.815006
58	3.60049	32.39951	15.30208	8.697916	5.369152	6.630848	2.814145	8.185855	2.750937	7.249063
59	4.840475	31.15953	20.57202	3.427982	7.218252	4.781748	3.783317	7.216683	3.69834	6.30166
60	5.485656	30.51434	23.31404	0.685962	8.180364	3.819636	4.287591	6.712409	4.191288	5.808712
61	4.500473	31.49953	19.12701	4.872988	6.711232	5.288768	3.517572	7.482428	3.438564	6.561436
62	5.394895	30.6051	22.9283	1.071696	8.045019	3.954981	4.216653	6.783347	4.121942	5.878058
MIN	2.98	30.31	12.65	0.00	4.44	3.52	2.33	6.56	2.27	5.66
MAX	5.69	33.02	24.17	11.35	8.48	7.56	4.44	8.67	4.34	7.73
MEAN	4.27	31.73	18.16	5.84	6.37	5.63	3.34	7.66	3.27	6.73
MEDIAN	4.25	31.75	18.05	5.95	6.33	5.67	3.32	7.68	3.24	6.76

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## APPENDIX E. BASE ‘C’ TRANSIT AND ON-STATION STATISTICS

NON-PENETRATING SCENARIO										
MISSION AREA	C									
	RQ-4		RQ-1		P-3		RC-135		U-2	
	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA
1	3.971865	32.02814	16.88043	7.119575	5.922956	6.077044	3.104411	7.895589	3.034683	6.965317
2	3.527194	32.47281	14.99058	9.009423	5.259851	6.740149	2.756857	8.243143	2.694935	7.305065
3	3.114286	32.88571	13.23572	10.76428	4.644111	7.355889	2.434128	8.565872	2.379455	7.620545
4	2.735166	33.26483	11.62445	12.37555	4.078756	7.921244	2.137807	8.862193	2.089789	7.910211
5	2.38478	33.61522	10.13532	13.86468	3.556251	8.443749	1.863945	9.136055	1.822079	8.177921
6	2.07772	33.92228	8.830309	15.16969	3.098354	8.901646	1.623947	9.376053	1.587471	8.412529
7	1.835853	34.16415	7.802376	16.19762	2.737676	9.262324	1.434904	9.565096	1.402674	8.597326
8	2.07772	33.92228	8.830309	15.16969	3.098354	8.901646	1.623947	9.376053	1.587471	8.412529
9	2.38478	33.61522	10.13532	13.86468	3.556251	8.443749	1.863945	9.136055	1.822079	8.177921
10	2.735166	33.26483	11.62445	12.37555	4.078756	7.921244	2.137807	8.862193	2.089789	7.910211
11	3.114286	32.88571	13.23572	10.76428	4.644111	7.355889	2.434128	8.565872	2.379455	7.620545
12	3.470784	32.52922	14.75083	9.24917	5.17573	6.82427	2.712766	8.287234	2.651835	7.348165
13	3.867275	32.13272	16.43592	7.564079	5.76699	6.23301	3.022664	7.977336	2.954772	7.045228
24	4.416535	31.58346	18.77027	5.229726	6.586061	5.413939	3.451966	7.548034	3.374431	6.625569
MIN	1.84	31.58	7.80	5.23	2.74	5.41	1.43	7.55	1.40	6.63
MAX	4.42	34.16	18.77	16.20	6.59	9.26	3.45	9.57	3.37	8.60
MEAN	2.98	33.02	12.66	11.34	4.44	7.56	2.33	8.67	2.28	7.72
MEDIAN	2.92	33.08	12.43	11.57	4.36	7.64	2.29	8.71	2.23	7.77

PENETRATING SCENARIO										
MISSION AREA	C									
	RQ-4		RQ-1		P-3		RC-135		U-2	
	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA
1	3.867275	32.13272	16.43592	7.564079	5.76699	6.23301	3.022664	7.977336	2.954772	7.045228
2	3.470784	32.52922	14.75083	9.24917	5.17573	6.82427	2.712766	8.287234	2.651835	7.348165
3	3.114286	32.88571	13.23572	10.76428	4.644111	7.355889	2.434128	8.565872	2.379455	7.620545
4	2.735166	33.26483	11.62445	12.37555	4.078756	7.921244	2.137807	8.862193	2.089789	7.910211
5	2.38478	33.61522	10.13532	13.86468	3.556251	8.443749	1.863945	9.136055	1.822079	8.177921
6	2.07772	33.92228	8.830309	15.16969	3.098354	8.901646	1.623947	9.376053	1.587471	8.412529
7	1.835853	34.16415	7.802376	16.19762	2.737676	9.262324	1.434904	9.565096	1.402674	8.597326
8	2.07772	33.92228	8.830309	15.16969	3.098354	8.901646	1.623947	9.376053	1.587471	8.412529
9	2.38478	33.61522	10.13532	13.86468	3.556251	8.443749	1.863945	9.136055	1.822079	8.177921
10	2.735166	33.26483	11.62445	12.37555	4.078756	7.921244	2.137807	8.862193	2.089789	7.910211
11	3.114286	32.88571	13.23572	10.76428	4.644111	7.355889	2.434128	8.565872	2.379455	7.620545
12	3.470784	32.52922	14.75083	9.24917	5.17573	6.82427	2.712766	8.287234	2.651835	7.348165
13	3.867275	32.13272	16.43592	7.564079	5.76699	6.23301	3.022664	7.977336	2.954772	7.045228
24	4.273261	31.72674	18.16136	5.838639	6.372407	5.627593	3.339983	7.660017	3.264964	6.735036
51	3.717666	32.28233	15.80008	8.199919	5.543888	6.456112	2.90573	8.09427	2.840464	7.159536
52	4.221248	31.77875	17.9403	6.059697	6.294843	5.705157	3.299329	7.700671	3.225223	6.774777
53	2.899745	33.10026	12.32392	11.67608	4.324181	7.675819	2.266442	8.733558	2.215535	7.784465
54	3.526173	32.47383	14.98623	9.013767	5.258327	6.741673	2.756058	8.243942	2.694154	7.305846
55	4.764325	31.23568	20.24838	3.75162	7.104695	4.895305	3.723798	7.276202	3.640158	6.359842
56	3.970271	32.02973	16.87365	7.12635	5.920579	6.079421	3.103165	7.896835	3.033465	6.966535
57	3.017406	32.98259	12.82397	11.17603	4.49964	7.50036	2.358406	8.641594	2.305434	7.694566
58	2.223352	33.77665	9.449244	14.55076	3.315524	8.684476	1.737773	9.262227	1.698741	8.301259
59	3.526173	32.47383	14.98623	9.013767	5.258327	6.741673	2.756058	8.243942	2.694154	7.305846
60	4.221248	31.77875	17.9403	6.059697	6.294843	5.705157	3.299329	7.700671	3.225223	6.774777
61	2.899745	33.10026	12.32392	11.67608	4.324181	7.675819	2.266442	8.733558	2.215535	7.784465
62	3.717666	32.28233	15.80008	8.199919	5.543888	6.456112	2.90573	8.09427	2.840464	7.159536
MIN	1.84	31.24	7.80	3.75	2.74	4.90	1.43	7.28	1.40	6.36
MAX	4.76	34.16	20.25	16.20	7.10	9.26	3.72	9.57	3.64	8.60
MEAN	3.24	32.76	13.75	10.25	4.82	7.18	2.53	8.47	2.47	7.53
MEDIAN	3.29	32.71	13.99	10.01	4.91	7.09	2.57	8.43	2.52	7.48

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## APPENDIX F. BASE ‘D’ TRANSIT AND ON-STATION STATISTICS

NON-PENETRATING SCENARIO										
MISSION AREA	D									
	RQ-4		RQ-1		P-3		RC-135		U-2	
	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA
1	5.145959	30.85404	21.87032	2.129675	7.673798	4.326202	4.022084	6.977916	3.931744	6.068256
2	4.701288	31.29871	19.98048	4.019524	7.010693	4.989307	3.674529	7.325471	3.591996	6.408004
3	4.28838	31.71162	18.22562	5.774384	6.394953	5.605047	3.3518	7.6482	3.276515	6.723485
4	3.828111	32.17189	16.26947	7.730528	5.708587	6.291413	2.992053	8.007947	2.924849	7.075151
5	3.367842	32.63216	14.31333	9.686673	5.02222	6.97778	2.632307	8.367693	2.573182	7.426818
6	2.907572	33.09243	12.35718	11.64282	4.335854	7.664146	2.27256	8.72744	2.221516	7.778484
7	2.447303	33.5527	10.40104	13.59896	3.649487	8.350513	1.912813	9.087187	1.86985	8.13015
8	1.987132	34.01287	8.445312	15.55469	2.963267	9.036733	1.553143	9.446857	1.518258	8.481742
9	1.52702	34.47298	6.489837	17.51016	2.277136	9.722864	1.19352	9.80648	1.166712	8.833288
10	1.067044	34.93296	4.534939	19.46506	1.591207	10.40879	0.834002	10.166	0.81527	9.18473
11	0.607513	35.39249	2.581931	21.41807	0.905941	11.09406	0.474833	10.52517	0.464167	9.535833
12	0.596622	35.40338	2.535642	21.46436	0.889699	11.1103	0.46632	10.53368	0.455846	9.544154
13	0.850396	35.1496	3.614183	20.38582	1.268134	10.73187	0.66467	10.33533	0.649741	9.350259
24	5.590629	30.40937	23.76017	0.239827	8.336903	3.663097	4.369638	6.630362	4.271492	5.728508
MIN	0.60	30.41	2.54	0.24	0.89	3.66	0.47	6.63	0.46	5.73
MAX	5.59	35.40	23.76	21.46	8.34	11.11	4.37	10.53	4.27	9.54
MEAN	2.78	33.22	11.81	12.19	4.14	7.86	2.17	8.83	2.12	7.88
MEDIAN	2.68	33.32	11.38	12.62	3.99	8.01	2.09	8.91	2.05	7.95

PENETRATING SCENARIO										
MISSION AREA	D									
	RQ-4		RQ-1		P-3		RC-135		U-2	
	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA	TRANS.	ON-STA
1	3.932977	32.06702	16.71515	7.284848	5.864966	6.135034	3.074017	7.925983	3.004971	6.995029
2	3.886012	32.11399	16.51555	7.484448	5.794931	6.205069	3.037309	7.962691	2.969088	7.030912
3	3.887699	32.1123	16.52272	7.477278	5.797446	6.202554	3.038628	7.961372	2.970377	7.029623
4	3.492483	32.50752	14.84305	9.156949	5.208088	6.791912	2.729726	8.270274	2.668414	7.331586
5	3.115182	32.88482	13.23952	10.76048	4.645447	7.354553	2.434828	8.565172	2.380139	7.619861
6	2.763146	33.23685	11.74337	12.25663	4.120481	7.879519	2.159676	8.840324	2.111168	7.888832
7	2.447303	33.5527	10.40104	13.59896	3.649487	8.350513	1.912813	9.087187	1.86985	8.13015
8	1.987132	34.01287	8.445312	15.55469	2.963267	9.036733	1.553143	9.446857	1.518258	8.481742
9	1.52702	34.47298	6.489837	17.51016	2.277136	9.722864	1.19352	9.80648	1.166712	8.833288
10	1.067044	34.93296	4.534939	19.46506	1.591207	10.40879	0.834002	10.166	0.81527	9.18473
11	0.607513	35.39249	2.581931	21.41807	0.905941	11.09406	0.474833	10.52517	0.464167	9.535833
12	0.596622	35.40338	2.535642	21.46436	0.889699	11.1103	0.46632	10.53368	0.455846	9.544154
13	0.850396	35.1496	3.614183	20.38582	1.268134	10.73187	0.66467	10.33533	0.649741	9.350259
24	4.02877	31.97123	17.12227	6.877728	6.007815	5.992185	3.148888	7.851112	3.078161	6.921839
51	3.551118	32.44888	15.09225	8.907749	5.295527	6.704473	2.775555	8.224445	2.713214	7.286786
52	3.178579	32.82142	13.50896	10.49104	4.739986	7.260014	2.484379	8.515621	2.428577	7.571423
53	2.89696	33.10304	12.31208	11.68792	4.320028	7.679972	2.264265	8.735735	2.213408	7.786592
54	2.773512	33.22649	11.78743	12.21257	4.135939	7.864061	2.167778	8.832222	2.119088	7.880912
55	2.928327	33.07167	12.44539	11.55461	4.366803	7.633197	2.288782	8.711218	2.237373	7.762627
56	2.485783	33.51422	10.56458	13.43542	3.706869	8.293131	1.942889	9.057111	1.89925	8.10075
57	2.229016	33.77098	9.473319	14.52668	3.323971	8.676029	1.7422	9.2578	1.703069	8.296931
58	2.312321	33.68768	9.827362	14.17264	3.448197	8.551803	1.807311	9.192689	1.766717	8.233283
59	1.858833	34.14117	7.90004	16.09996	2.771944	9.228056	1.452865	9.547135	1.420232	8.579768
60	2.028526	33.97147	8.621235	15.37876	3.024995	8.975005	1.585497	9.414503	1.549885	8.450115
61	1.550462	34.44954	6.589464	17.41054	2.312093	9.687907	1.211842	9.788158	1.184623	8.815377
62	1.145201	34.8548	4.867105	19.1329	1.707756	10.29224	0.89509	10.10491	0.874985	9.125015
MIN	0.60	31.97	2.54	6.88	0.89	5.99	0.47	7.85	0.46	6.92
MAX	4.03	35.40	17.12	21.46	6.01	11.11	3.15	10.53	3.08	9.54
MEAN	2.43	33.57	10.32	13.68	3.62	8.38	1.90	9.10	1.86	8.14
MEDIAN	2.47	33.53	10.48	13.52	3.68	8.32	1.93	9.07	1.88	8.12



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## APPENDIX G. NON-PENETRATING COVERAGE MODEL

### Summary of Fit

RSquare	0.780377
RSquare Adj	0.763686
Root Mean Square Error	0.008541
Mean of Response	0.485819
Observations (or Sum Wgts)	270

### Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	19	0.06479516	0.003410	46.7534
Error	250	0.01823541	0.000073	Prob > F
C. Total	269	0.08303057		<.0001 *

### Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.4762323	0.002843	167.51	<.0001 *
A RQ-4	-0.002767	0.000534	-5.18	<.0001 *
A RQ-1	-0.000885	0.000285	-3.10	0.0021 *
A RC-135	0.0039884	0.000535	7.45	<.0001 *
A U-2	0.0056309	0.000536	10.50	<.0001 *
B RQ-4	-0.002767	0.000541	-5.12	<.0001 *
B RC-135	-0.000835	0.000538	-1.55	0.1219
B U-2	0.0035851	0.000534	6.71	<.0001 *
C RQ-4	-0.002511	0.000531	-4.73	<.0001 *
C U-2	0.0058404	0.000531	10.99	<.0001 *
D RQ-4	-0.001957	0.000529	-3.70	0.0003 *
D U-2	0.0074843	0.000532	14.07	<.0001 *
OPT INT	-0.004388	0.000361	-12.15	<.0001 *
(A RQ-4-1.52963)*(B RC-135-1.52963)	-0.002434	0.000522	-4.66	<.0001 *
(A RC-135-1.52963)*(D RQ-4-1.52963)	-0.001769	0.000518	-3.41	0.0007 *
(B RC-135-1.52963)*(D RQ-4-1.52963)	-0.001793	0.000535	-3.35	0.0009 *
(C RQ-4-1.52963)*(D U-2-1.52963)	-0.002549	0.000504	-5.05	<.0001 *
(B RQ-4-1.52963)*(B RQ-4-1.52963)	0.001986	0.000574	3.46	0.0006 *
(C U-2-1.52963)*(C U-2-1.52963)	-0.001624	0.00057	-2.85	0.0047 *
(D RQ-4-1.52963)*(D RQ-4-1.52963)	0.0030399	0.000559	5.44	<.0001 *

### Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob> t
Intercept	0.4823027	0.001085	444.69	0.0000 *
A RQ-4	-0.00415	0.000802	-5.18	<.0001 *
A RQ-1	-0.002655	0.000856	-3.10	0.0021 *
A RC-135	0.0059826	0.000803	7.45	<.0001 *
A U-2	0.0084464	0.000805	10.50	<.0001 *
B RQ-4	-0.00415	0.000811	-5.12	<.0001 *
B RC-135	-0.001253	0.000807	-1.55	0.1219
B U-2	0.0053776	0.000801	6.71	<.0001 *
C RQ-4	-0.003766	0.000796	-4.73	<.0001 *
C U-2	0.0087605	0.000797	10.99	<.0001 *
D RQ-4	-0.002936	0.000793	-3.70	0.0003 *
D U-2	0.0112265	0.000798	14.07	<.0001 *
OPT INT	-0.011061	0.00091	-12.15	<.0001 *
(A RQ-4-1.52963)*(B RC-135-1.52963)	-0.005477	0.001175	-4.66	<.0001 *
(A RC-135-1.52963)*(D RQ-4-1.52963)	-0.00398	0.001166	-3.41	0.0007 *
(B RC-135-1.52963)*(D RQ-4-1.52963)	-0.004035	0.001204	-3.35	0.0009 *
(C RQ-4-1.52963)*(D U-2-1.52963)	-0.005736	0.001135	-5.05	<.0001 *
(B RQ-4-1.52963)*(B RQ-4-1.52963)	0.0044685	0.001292	3.46	0.0006 *
(C U-2-1.52963)*(C U-2-1.52963)	-0.003654	0.001282	-2.85	0.0047 *
(D RQ-4-1.52963)*(D RQ-4-1.52963)	0.0068398	0.001258	5.44	<.0001 *

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## APPENDIX H. PENETRATING COVERAGE MODEL

### Summary of Fit

RSquare	0.709558
RSquare Adj	0.677153
Root Mean Square Error	0.031621
Mean of Response	0.592963
Observations (or Sum Wgts)	270

### Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	27	0.59115961	0.021895	21.8968
Error	242	0.24197826	0.001000	Prob > F
C. Total	269	0.83313787		<.0001*

### Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.3606258	0.011655	30.94	<.0001*
A RQ-4	0.0054156	0.001988	2.72	0.0069*
A RQ-1	0.0065338	0.001058	6.17	<.0001*
A P-3	0.0061525	0.001063	5.79	<.0001*
A U-2	0.0059377	0.001998	2.97	0.0033*
B RQ-4	0.0080442	0.00197	4.08	<.0001*
B P-3	0.003962	0.001046	3.79	0.0002*
B U-2	0.0064787	0.001974	3.28	0.0012*
C RQ-4	0.0107559	0.001982	5.43	<.0001*
C P-3	0.0022811	0.001052	2.17	0.0311*
C U-2	0.0050889	0.001977	2.57	0.0107*
D RQ-4	0.0063526	0.001993	3.19	0.0016*
D RQ-1	0.003488	0.001069	3.26	0.0013*
D P-3	0.0081541	0.001063	7.67	<.0001*
D RC-135	0.0071914	0.002009	3.58	0.0004*
D U-2	0.0136722	0.002008	6.81	<.0001*
OPT INT	0.0139716	0.001338	10.45	<.0001*
(A RQ-4-1.52963)*(OPT INT-3.46986)	-0.003346	0.001438	-2.33	0.0208*
(A RQ-1-3.05926)*(D U-2-1.52963)	0.0032962	0.001103	2.99	0.0031*
(A P-3-3.05926)*(C RQ-4-1.52963)	0.0009105	0.000949	0.96	0.3383
(A U-2-1.52963)*(D RQ-4-1.52963)	-0.004324	0.001949	-2.22	0.0274*
(B RQ-4-1.52963)*(B U-2-1.52963)	-0.003686	0.002221	-1.66	0.0983
(C RQ-4-1.52963)*(OPT INT-3.46986)	-0.003959	0.001359	-2.91	0.0039*
(C P-3-3.05926)*(C U-2-1.52963)	-0.001152	0.001217	-0.95	0.3448
(D RQ-1-3.05926)*(D RC-135-1.52963)	-0.003878	0.001108	-3.50	0.0005*
(D P-3-3.05926)*(OPT INT-3.46986)	0.0006726	0.000747	0.90	0.3688
(B P-3-3.05926)*(B P-3-3.05926)	-0.001511	0.000673	-2.25	0.0256*
(D U-2-1.52963)*(D U-2-1.52963)	-0.008468	0.00225	-3.76	0.0002*

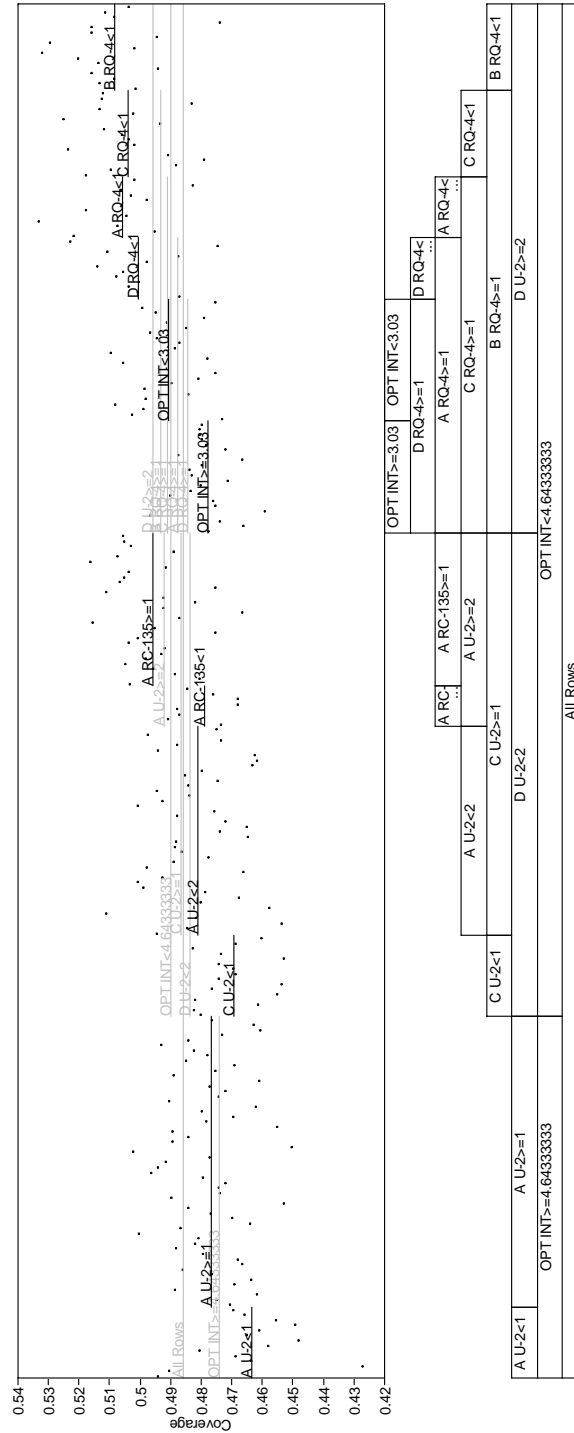
### Scaled Estimates

Continuous factors centered by mean, scaled by range/2

Term	Scaled Estimate	Std Error	t Ratio	Prob> t
Intercept	0.6080798	0.003295	184.53	<.0001*
A RQ-4	0.0081234	0.002981	2.72	0.0069*
A RQ-1	0.0196014	0.003174	6.17	<.0001*
A P-3	0.0184576	0.003189	5.79	<.0001*
A U-2	0.0089066	0.002997	2.97	0.0033*
B RQ-4	0.0120663	0.002954	4.08	<.0001*
B P-3	0.011886	0.003139	3.79	0.0002*
B U-2	0.009718	0.002962	3.28	0.0012*
C RQ-4	0.0161338	0.002973	5.43	<.0001*
C P-3	0.0068433	0.003156	2.17	0.0311*
C U-2	0.0076333	0.002966	2.57	0.0107*
D RQ-4	0.0095289	0.002989	3.19	0.0016*
D RQ-1	0.010464	0.003207	3.26	0.0013*
D P-3	0.0244623	0.00319	7.67	<.0001*
D RC-135	0.010787	0.003013	3.58	0.0004*
D U-2	0.0205083	0.003012	6.81	<.0001*
OPT INT	0.0352201	0.003372	10.45	<.0001*
(A RQ-4-1.52963)*(OPT INT-3.46986)	-0.01265	0.005438	-2.33	0.0208*
(A RQ-1-3.05926)*(D U-2-1.52963)	0.0148331	0.004963	2.99	0.0031*
(A P-3-3.05926)*(C RQ-4-1.52963)	0.0040974	0.004271	0.96	0.3383
(A U-2-1.52963)*(D RQ-4-1.52963)	-0.009729	0.004384	-2.22	0.0274*
(B RQ-4-1.52963)*(B U-2-1.52963)	-0.008293	0.004998	-1.66	0.0983
(C RQ-4-1.52963)*(OPT INT-3.46986)	-0.014971	0.005138	-2.91	0.0039*
(C P-3-3.05926)*(C U-2-1.52963)	-0.005185	0.005477	-0.95	0.3448
(D RQ-1-3.05926)*(D RC-135-1.52963)	-0.017453	0.004984	-3.50	0.0005*
(D P-3-3.05926)*(OPT INT-3.46986)	0.0050865	0.00565	0.90	0.3688
(B P-3-3.05926)*(B P-3-3.05926)	-0.013603	0.006058	-2.25	0.0256*
(D U-2-1.52963)*(D U-2-1.52963)	-0.019052	0.005062	-3.76	0.0002*

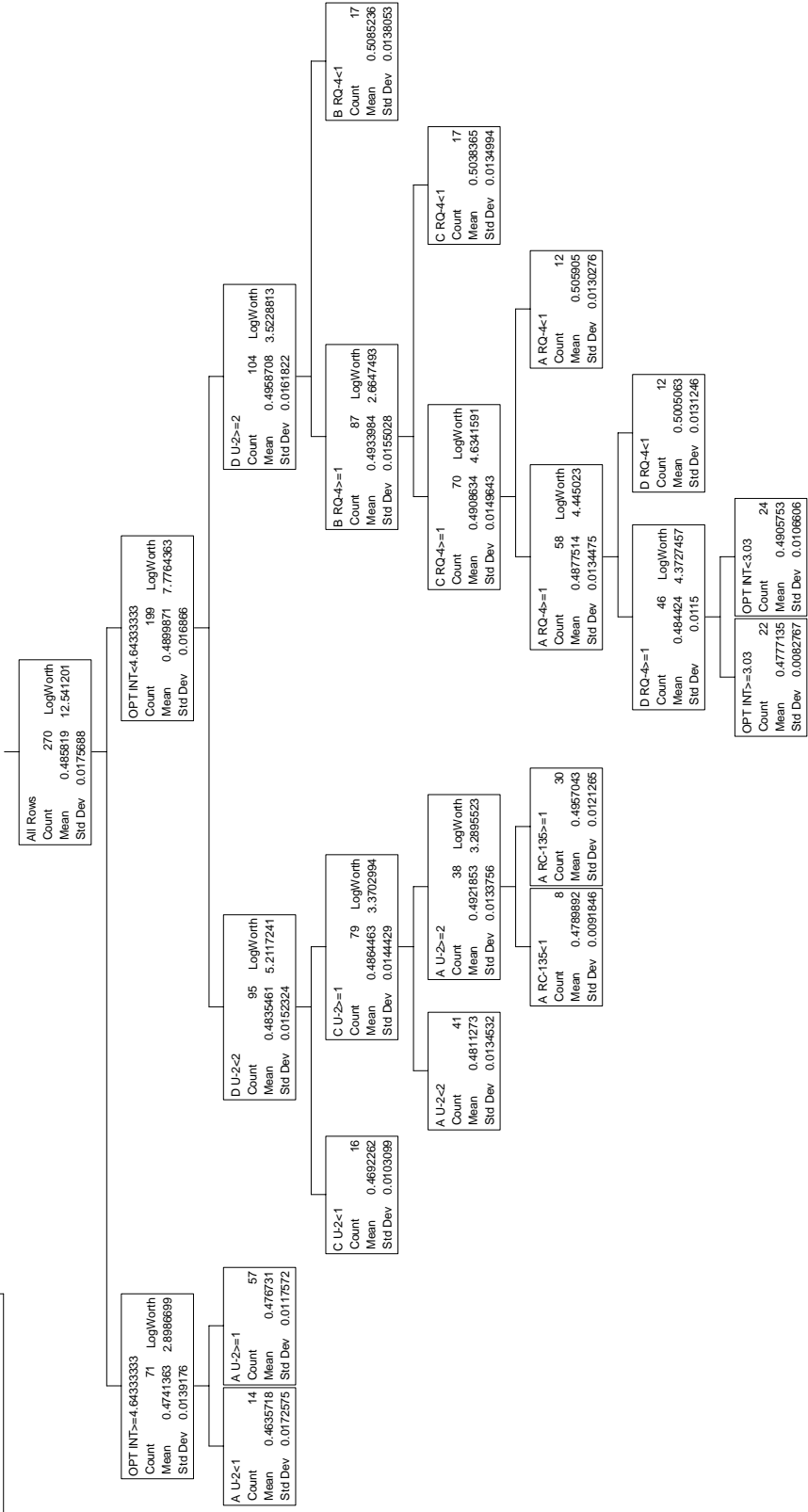
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## APPENDIX I. REGRESSION TREE FOR NON-PENETRATING COVERAGE

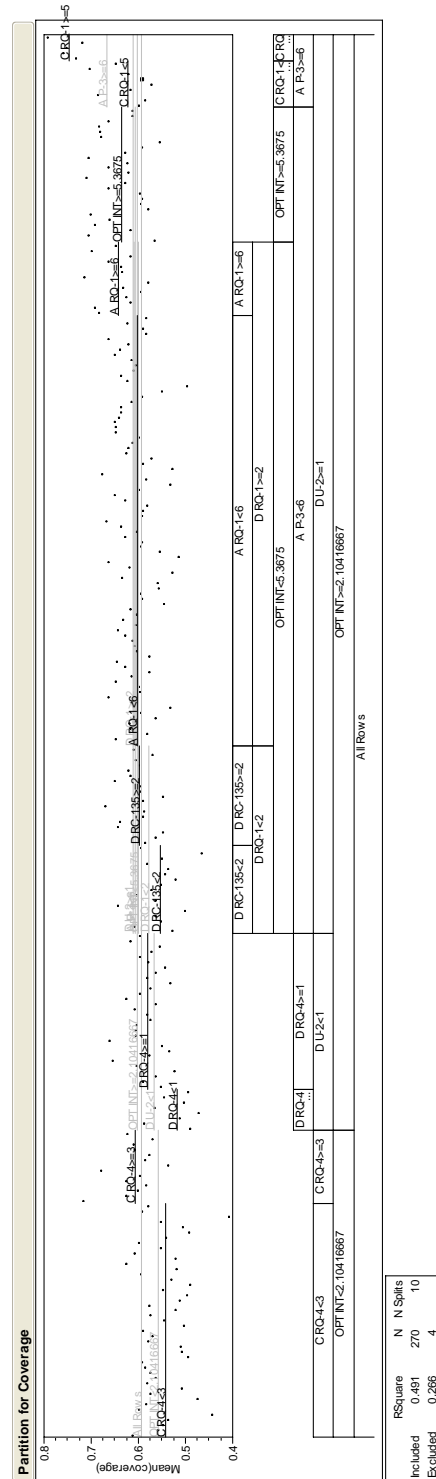


# Partition for Coverage

RSquare	N	N Splits
Included	0.529	270
Excluded	0.099	4



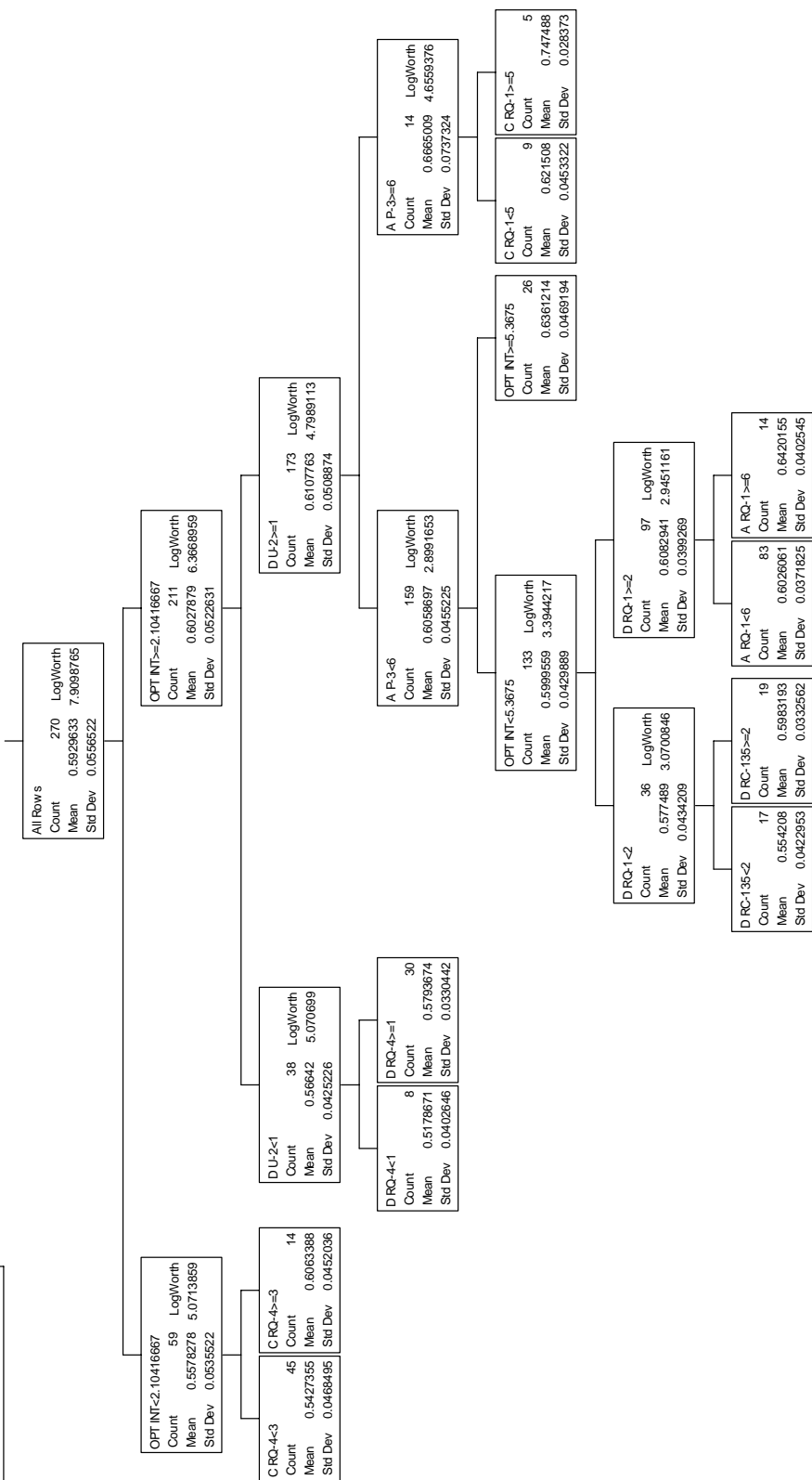
## APPENDIX J. REGRESSION TREE FOR PENETRATING COVERAGE





### Partition for Coverage

	RSquare	N	N Splits
Included	0.491	270	10
Excluded	0.266	4	



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